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Determining Geotechnical and Hydrogeological Parameters Using Downhole Geophysics in the Canadian Plains

Phase 1 Report

A REVIEW OF POTENTIAL APPLICATIONS

VOLUME I

April 1987

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on behalf of the

Downhole Geophysics joint venture research group

119 pp

MICROMEDIA

EXECUTIVE SUMMARY

The Downhole Geophysics project resulted from the desire of several resource companies and geoscience consulting firms to improve the cost-to-data ratio of obtaining hydrogeological and geotechnical information for both coal and oil sands mining operations.

Proposals for joint industry and government research funding were prepared and submitted. The acceptance of these proposals for 50/50 industry/government funding by the Alberta and Canadian Governments resulted in the commencement of the project in November 1986. The project was divided into three phases, the results of the first Phase being reported here.

The objective of the first Phase is "to examine the current state of the art and the published literature concerning the use of downhole geophysics to obtain various geotechnical and hydrogeological parameters." This examination was conducted by various members of the project joint venture and consolidated into this report of the Phase 1 work.

The geotechnical and hydrogeological parameters of interest for the project were developed by the geotechnical and hydrogeological working committees. The work was then divided into six main areas to be addressed. These areas included:

Literature search
Review of geophysical instrumentation
Review of geotechnical papers
Review of hydrogeological papers
Current research and developments
Software for parameter determination

The literature search was based on an extensive list of keywords developed by the participants and the working committees with input from an external panel of experts. Several searches were required with various search strategies to generate a manageable citation list that provided reasonably complete coverage. In all over 1400 citations were produced from nine data bases.

Elimination of duplications and clearly irrelevant citations reduced this to over 430 citations.

This citation list was inspected by various participants and experts to produce a list of desired papers for detailed reviews. One hundred and thirty seven papers were obtained and reviewed by the project participants and authors.

Three main classes of geophysical instrumentation were identified along with four other measurement systems which, while not strictly geophysical, can be used for determining some of the parameters of interest to this study.

These seven groups of instrumentation include:

Electrical	- eleven methods of which six appear to have potential for further study
Nuclear	- three methods
Acoustic	- three methods
Caliper	- direct hole shape measurement
Temperature	- direct measurement of borehole fluid temperature
Flow	- direct measurement of fluid flow in the hole
Image	- both visual and acoustic images of the borehole walls.

In the review of potential geotechnical applications, it is apparent that several of the desired geotechnical parameters can be determined from currently available geophysical logging and interpretation techniques. These include better use of dipmeter logs (three point micro resistivity) for structural interpretation and possibly joint set identification. Density, porosity and in some cases mineralogy can be obtained from the gamma-gamma, neutron and natural gamma logs respectively.

Acoustic methods such as transit time, vertical seismic profiling and cross-hole seismic logging have potential to provide information concerning density, dynamic elastic properties of rock, faults, fractures and lithological surfaces.

Radar's high penetrating power suggests that it will provide structural information between the boreholes. The actual penetration, however, is very dependent on the local rock resistivities. As well, the requirement for a resistivity contrast along the structural feature of interest means that radar's effectiveness will be very site specific.

The review of geophysical applications for the determination of hydrogeological parameters reveals that the petroleum industry is well advanced in this area. The determination of porosity from neutron logs and permeability from resistivity and natural gamma logs (Archie's formula) are widely accepted in the oil and gas industry. The reliability of these interpretations has yet to be confirmed in the shallow fresh water borehole environment found in coal and oil sand exploration.

Flowmeters and temperature probes are reported to be able to provide information on the distribution of permeability within the borehole and the location of aquifers. Other potential uses include seepage evaluation in tailings dykes and dewatering efficiency testing.

Water quality determinations have been made through correlation of total dissolved solids and water resistivity. Work has also been done using a small diameter induction proble for measuring changes in water quality over time.

Current research into geophysical instrumentation and methods reveals that there are a large number of groups working in this area. Several companies are improving and refining geophysical probes for better accuracy and smaller diameter holes. This includes combining several measurement systems into single probes to reduce the number of logging runs requied.

Borehole systems for radar, VHF radio imaging, magnetic susceptibility and low frequency electromagnetics are being developed and tested with commercial products available in some cases.

Work is being conducted on the possibility of measuring several geophysical properties while the borehole is being drilled. Besides the mechanical properties, gamma and resistivity measurements are currently being attempted.

There are many software packages available for manipulating and displaying various geophysical logs. Only a few of these, however, have inbuilt interpretation techniques for determining any of the desired geotechnical or hydrogeological parameters. The reliability of these few inbuilt routines has not yet been demonstrated in the plains sedimentary environments commonly found in coal and oil sand exploration and mining. Software will need to be selected that allows the users to develop their own interpretation techniques. This will require as much flexibility in the analysis and display of the various logs as is possible to obtain.

This "state-of-the-art" review of the use of borehole geophysics shows that there are techniques available to determine some of the geotechnical and hydrogeological parameters of interest. The reliability and effectiveness of these techniques in the shallow, soft rock typical of the western Canadian coal and oil sand mining situations has not been fully evaluated or in some cases even attempted.

It is recommended that interpretation techniques to determine various parameters of interest be tried using one or two computer software packages. Data for this work should come from currently available geophysical and laboratory data. A recommendation on which additional geophysical log data needs to be collected for further work should be developed. The progress of ongoing research by other groups should continue to be monitored to enable adoption of the best and most current techniques in the determination of geotechnical and hydrogeological parameters.

PREFACE

This report reviews the literature and state of the art in the use of downhole geophysics to determine geotechnical and hydrogeological parameters. The results reported in the following chapters are based on the work completed as Phase I of the Downhole Geophysics Project undertaken as a joint industry/government research investigation. The project joint venture is funded by the following companies and organizations:

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The work plan organization, control and reporting was supervised by a Geotechnical Committee chaired by Mr. Geoff Jenkins of Manalta Coal and a Hydrogeological Committee chaired by Mr. Andrew Hickinbotham of TransAlta Utilities.

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This report and its contents, the research project in respect of which it is submitted and the technology produced or demonstrated in the research project do not necessarily reflect the views of the Government of Alberta, its officers, employees or agents (or of the Alberta/Canada Energy Resources Research Fund Committee) or of the Members of the Office.

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DOWNHOLE GEOPHYSICS PROJECT

TABLE OF CONTENTS

	PAGE
EXECUTIVE SUMMARY	i
PREFACE	v
ACKNOWLEDGEMENT/DISCLAIMER	viii
1. INTRODUCTION	1
1.1 Project Formation	1
1.2 Background	1
1.3 Objectives	3
1.3.1 Objectives of Total Research Program	3
1.3.2 Objectives of Phase 1 (1986/1987)	3
2. PROJECT APPROACH	5
2.1 Scope	5
2.2 Work Plan	6
3. LITERATURE SEARCH	9
3.1 Keyword List Development	9
3.2 Computerized Database Search	9
3.2.1 Scope of Search	9
3.2.2 Search Products	9
3.2.3 Strategy of Computerized Search	10
3.3 Abstract and Paper Selection	11
4. GEOPHYSICAL INSTRUMENTATION	12
4.1 Introduction	12
4.2 Electrical Methods	13
4.3 Nuclear Methods	14
4.4 Acoustic Methods	15
4.5 Caliper Logging	16
4.6 Thermal and Flow Logging	16
4.7 Television and Acoustic Televiewer	17

TABLE OF CONTENTS (Cont'd.)

		PAGE
5.	REVIEW OF GEOTECHNICAL APPLICATIONS	18
5.1	Purpose of Review	18
5.2	Geotechnical Parameters and Investigation Methods	18
5.2.1	Geotechnical Parameters of Interest	18
5.2.2	Investigation Methods	18
5.2.3	Evaluation of Methods	20
5.3	Summary of Relevant papers	20
5.3.1	Borehole Televiewer	20
5.3.2	Testing and Calibration of Downhole Probes	20
5.3.3	Borehole Radar	21
5.3.4	Holography	21
5.3.5	Dipmeter	22
5.3.6	Combination Probes	22
5.3.7	Sonic, Tube Wave (VSP), Acoustic and Geotomographic Methods	23
5.3.8	Gravity Probes	25
5.3.9	Neutron-Neutron Probes	25
5.3.10	Gamma-Gamma Density	26
5.4	Results	27
5.5	Conclusions	28
6.	REVIEW OF HYDROGEOLOGICAL APPLICATIONS	29
6.1	Introduction	29
6.2	Current Uses	29
6.2.1	Borehole Damage and Drilling Effects	29
6.2.2	Permeability	31
6.2.3	Pressure Head/Pore Pressure	36
6.2.4	Porosity/Storativity/Specific Yield	37
6.2.5	Water Quality	38
6.2.6	Degree of Saturation and Water Quality	38
6.3	Summary and Conclusions	39
7.	CURRENT RESEARCH AND DEVELOPMENTS	40
7.1	Research Groups	40
7.2	Interview Method	40
7.3	Measured Parameters	40
7.4	Geophysical Probes	41
7.4.1	Impulse Radar Methods	41
7.4.2	Neutron-Neutron Probe	41
7.4.3	Gamma-Gamma Probe	42
7.4.4	Cross-hole Seismic	42
7.4.5	Magnetic Susceptilibity	43
7.4.6	Radio Imaging Method (RIM)	43

TABLE OF CONTENTS (Cont'd.)

		PAGE
7.4.7	Borehole to Borehole Electromagnetic Systems	43
7.4.8	Multi-Probe System	44
7.4.9	Heat Pulse Flowmeter	44
7.4.10	Acoustic Televiewers	44
7.4.11	Dip Meter Probe	45
7.4.12	Formation Microscanner Service	45
7.4.13	Measurement While Drilling (MWD)	45
7.4.14	Low Frequency EM Probe	46
7.4.15	Other Applications	46
7.5	Summary	46
8.	SOFTWARE FOR PARAMETER DETERMINATION	47
9.	SUMMARY AND CONCLUSIONS	52
9.1	General	52
9.2	Parameters and Probes	53
9.3	Data Manipulation Software	54
10.	RECOMMENDATIONS	57
11.	LIST OF REFERENCES	58

APPENDICIES

1. Project Organization and Management
2. Developed Key Word List
3. Equipment Suppliers and Researchers Contacted
4. Geophysical Logging Equipment by Manufacturer

VOLUME II

5. Paper Reviews

1. INTRODUCTION

1.1 Project Formation

The Downhole Geophysics project resulted from the desire of several resource companies to reduce the cost of obtaining hydrogeological and geotechnical information required for both coal and oil sands mining operations.

Several of the participants were involved in a previous research project to evaluate the potential of using surface geophysics to aid in coal exploration. The success of this project provided the incentive to form a research project to explore various means of obtaining geotechnical and hydrogeological information from downhole geophysics. Discussions with potential participants in 1985 led to the formation of the Downhole Geophysics Joint Venture Research Project. Because of the participants' interest in both oil sands and coal mining, the project was developed to examine the potential of obtaining geotechnical and hydrogeological parameters in both coal and oilsands formations and overburden. The details of the project organization and management are described in Appendix 1.

Proposals for joint industry and government research funding were prepared and submitted in the spring of 1986 to the Alberta Office of Coal Research and Technology and to Supply and Services Canada to fund the coal and oil-sands portions of the work respectively on a 50/50 basis with the industry particpants. Technical acceptance of the project by the funding agencies occurred in the summer of 1986 with detailed work commencing in November 1986 when financial approvals were completed.

1.2 Background

Mining companies and geoscience consulting firms aim to reduce costs, maintain high levels of safety and reduce the effects of the operation on the environment. In order to meet these objectives, mine planners require more geotechnical and hydrogeological information, which will enable them to predict highwall and spoil angles with greater confidence, reduce land disturbance,

predict and better handle disturbances to the local groundwater regime, assist in equipment selection and reclaim the mined out areas in a faster and more cost efficient manner.

The Alberta coal and oilsands deposits present a variety of geotechnical and hydrological problems as a result of their geological and geographical settings. They lie within poorly lithified clastic sediments that were deposited in deltaic, fluvial and estuarine environments during Jura-Cretaceous and younger times. The sediments are characterized by variations in lithology, both horizontally and vertically, over very short distances, so that it is difficult to correlate rock types, geotechnical characteristics, hydrogeological parameters, etc. without closely spaced drilling.

In addition to their stratigraphic complexity, the deposits have received varying degrees of tectonic deformation. The deposits of the Foothills and Mountain regions are strongly deformed, and are characterized by folds, a variety of types of faults, sheared zones, and joints. The Plains deposits (including oilsands) exhibit less faulting and little folding, but are jointed and in some areas have suffered glaciotectonic deformation, thereby contributing to their inherent weakness.

Pit slope stability, strip mine highwall stability, floor heave, floor trafficability and groundwater are major concerns in open-pit mining. Roof and floor conditions, stope dimensions, subsidence, groundwater and pillar strength are critical in underground mining.

The current methods of obtaining geotechnical information require time consuming and costly core drilling and laboratory testing. Obtaining hydrogeological parameters also requires expensive field testing such as packer tests and long term pumping tests.

Most of the resource companies in Alberta currently drill open holes and geophysically log them to obtain the lithological information required to do overall structural geology and to delineate the reserves. Minimum core drilling and laboratory testing are done to obtain geotechnical information because of the high cost involved. This forces the mine designer to evaluate designs based on very

sparse data. To account for localized changes in structural geology, rock strength and friction forces when the data are limited, the designer usually uses higher factors of safety and limited pit wall angle changes. This can result in higher strip ratios than necessary on one hand and localized wall problems on the other.

Similarly, obtaining hydrogeological information such as permeability and piezometric heads requires specialized field testing. This information affects both geotechnical design considerations as well as requirements for in-pit and surface water handling. The need to forecast the effects of mining on the groundwater table and quality are mandatory in obtaining environmental approvals for mining.

If the geophysical logs currently being recorded could be interpreted to obtain some or all of the required geotechnical or hydrogeological data, or new downhole geophysical tools or methods developed, the mine planners would have a better data base upon which to formulate the required design decisions. As a result of the additional information available from the same exploration dollars, the increased confidence in the parameters could reduce mining costs, improve safety and better predict the environmental impacts.

1.3 Objectives

1.3.1 Objectives of the Total Research Program

As outlined in the original proposals the objectives of the research program are to "... improve... and develop new techniques of using borehole geophysical data to determine geotechnical and hydrogeological characteristics of subsurface materials."

1.3.2 Objectives of Phase 1 (1986/1987)

The total project was divided into three phases. The objective of Phase 1, conducted from November 1986 to March 1987, and reported here is "to examine the current state of the art and the published literature concerning the use of downhole geophysics to obtain various geotechnical and hydrogeological parameters."

The scope, objectives and methods of the subsequent phases will be modified to reflect the results and conclusions of the previous phases.

2. PROJECT APPROACH

2.1 Scope

The parameters which were considered in developing the detailed work plan and reviewing the information were selected by the Management, Geotechnical and Hydrogeological committees with help from external experts. These parameters are listed in Tables 1 and 2.

Table 1

Geotechnical Parameters

shear, tensile and compressive strengths
peak and residual cohesive strengths
angle of internal friction
modulus of elasticity
shear modulus
bulk modulus
Poisson's Ratio
confining stresses
lateral stress ratio
moisture content
density
strike and dip of structure, bedding and faults
ground temperature

Table 2

Hydrogeological Parameters

water table
pore pressure
aquifer and aquitard delination
fluid flow
permeability
transmissibility
porosity
saturation
specific yield
storage coefficient
fluid conductivity
gas/liquid ratio
water quality
fluid temperature

2.2 Work Plan

The work plan to meet the objective was developed jointly by the Geotechnical and Hydrogeological Committees. The project was broken up into various sections and stages because of the size of the project and the desire by some of the participants to conduct portions of the work themselves.

The first step was to define the keywords and conduct the literature searches. The keyword listing was compiled by the committees and circulated for revisions and additions. The revised master list of keywords was used to search various computerized data bases of publications.

The resulting list of citations was reviewed by the technical committees and the outside experts. From the citation list, relevant papers were identified and as many as possible were obtained for review by the geotechnical and hydrogeological working groups. This portion of the work is described in detail in Chapter 3.

The scientific papers collected were individually reviewed by the professional members of the working groups. The reviews were reported in a standard format and included the reviewer's opinion of the paper's importance to the project objectives (Appendix 5). The information obtained from the review of the papers was consolidated into Chapters 5 and 6.

A review was conducted to determine which geophysical equipment and interpretive software were the most capable of determining the geotechnical and hydrogeological parameters of interest. This information was obtained from commercial geophysical instrument manufacturers, geophysical service companies, users of geophysical services and researchers (see Appendicies 3 and 4). Additional sources of information were revealed through the literature reviews. The results of this work are reported in Chapters 4 and 8.

Experts doing research in these areas were contacted to obtain as much information as possible about current, unpublished work. Naturally there was some reluctance to discuss work that had potential for commercial development. The researchers were identified during a review of the recent developments reported in the literature and contacts with the various geophysical service and instrumentation companies. The results of this investigation are described in Chapter 7.

Close contact between the working groups resulted in a beneficial cross flow of data, where information uncovered by one reviewer was useful to one of the other working groups.

Upon completion of the working groups' reviews and reports for the chapters, the summary of conclusions and recommendations was prepared. The result is a concise report on Phase 1 of the Downhole Geophysics Project.

A diagram of the work-plan logic is attached as Figure 1.

DOWNHOLE GEOPHYSICS PROJECT
LOGIC DIAGRAM

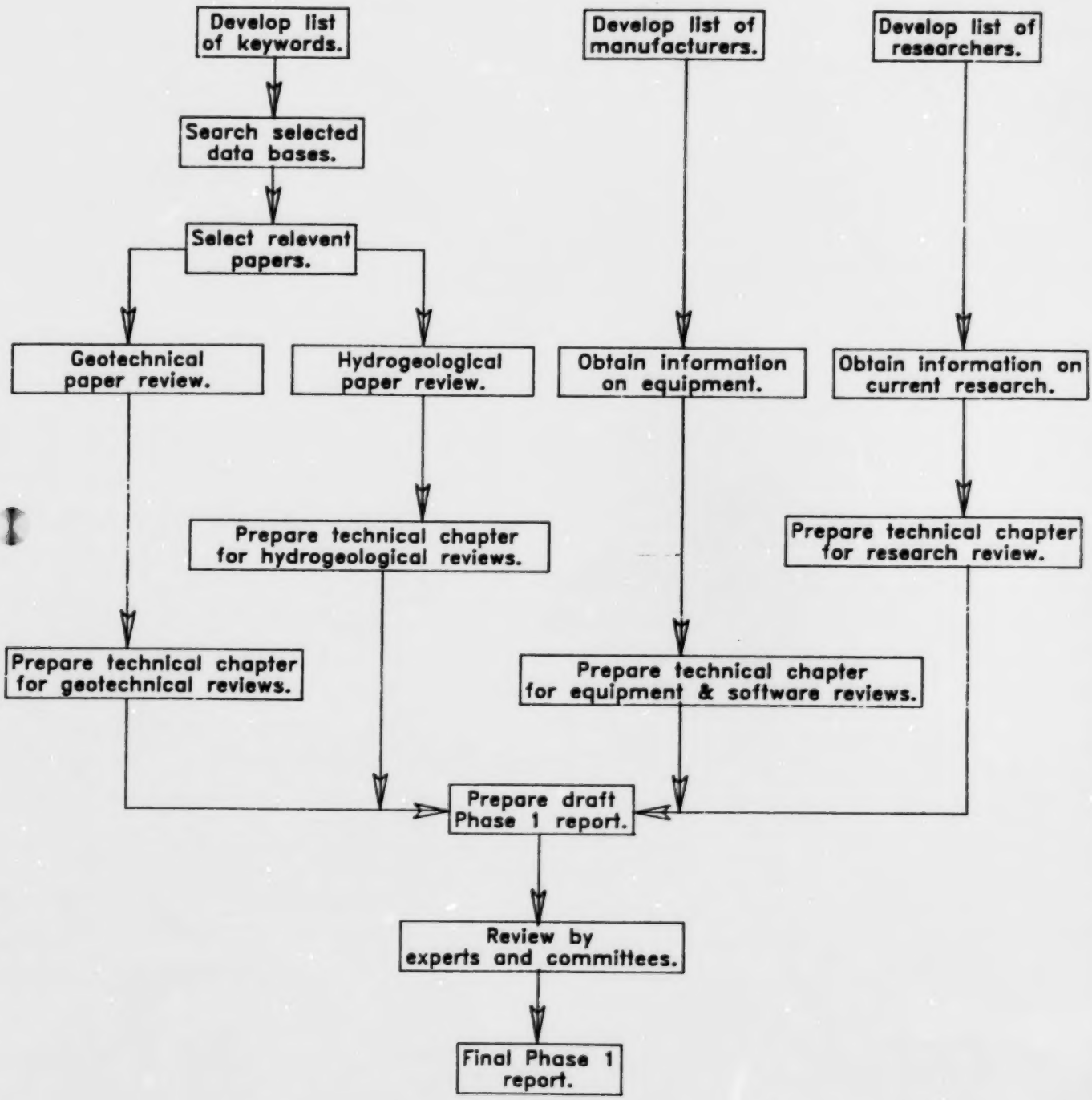
Develop list of keywords.
Develop list of manufacturers.
Develop list of researchers.
Search selected data bases.
Select relevent papers.
Geotechnical paper review.
Hydrogeological paper review.
Obtain information on equipment.
Obtain information on current research.
Prepare technical chapter for hydrogeological reviews.
Prepare technical chapter for research review.
Prepare technical chapter for geotechnical reviews.
Prepare technical chapter for equipment & software reviews.
Prepare draft Phase 1 report.
Review by experts and committees.
Final Phase 1 report.

FIG 1: Phase 1 Work–Plan

3. LITERATURE SEARCH

3.1 Key Word List Development

A list of key words encompassing the entire hydrogeologic and geotechnical interest in geophysics was developed by the hydrogeological and geotechnical committees with assistance from many of the project participants.

The complete key word list is found in Appendix 2.

3.2 Computerized Database Search

3.2.1 Scope of Search

The emphasis of the computerized search was to target all of the most pertinent literature contained in the databases. A large number of citations were targeted and the titles were reviewed to make up a final bibliographic listing.

The following observations suggest a thorough search:

1. An extensive listing was generated using a thorough search strategy on the most pertinent databases including Georef, GeoMechanical Abstracts and Tulsa.

2. The databases searched overlapped with approximately 30% duplication of citations.

3. Many of the articles and nearly all of the authors in reference lists of various participants were found by the searches.

3.2.2 Search Products

A search strategy was formulated using the complete key word list so that all pertinent databases could be searched efficiently. The key words were arranged strategically so that the computerized listing generated from the relevant key words would include all pertinent literature but remain manageable in size.

The original search performed by Syncrude generated an unmanageably large listing. Therefore, key word "borehole" was dropped and the term "downhole" retained. This produced a manageable listing but was felt to be too restrictive causing pertinent papers to be overlooked. Therefore, the ARC again searched the databases using a revised strategy that incorporated both the borehole and downhole terms.

After comprehensive, manageable citation lists were generated, the lists were reviewed and clearly irrelevant references were eliminated. The number of relevant references, chosen from the total number of citations generated by searches on the various databases, are given below.

Database Searched	Total # of Citations	# of Pertinent Citations
Alberta Oil Sands Index (AOST)	12	2
Geoarchive File 58)	176	65
GeoMechanical Abstracts	161	59
Georef (File 89) Syncrude downhole only*	200	41
Georef ARC Downhole & Borehole	529	112
NTIS (file 6) downhole only	180	19
Tulsa	171	28
GPO Monthly Catalogue	6	0
TOTAL	1,435	326

*A search was also conducted on the World Patents Index which targeted 293 references. This listing, restricted by using only the term downhole, was used for the equipment survey.

3.2.3 Strategy of Computerized Search

The search was performed using key words that indexed many citations.

An example of the search strategy performed on the Tulsa database is outlined below.

Key Word	# of Citations by individual key word
Borehole	10968
Downhole	1304
Log	9992
Tool	10236
Device	9253
Instrument	26286
Hydrol	6594

[borehole or downhole] and [Tool or device or Instrument or Log] and [Hydrol] results in 45 citations

[12087] and [49503] and [6594] results in [45]

3.3 Abstract and Paper Selection

The pertinent citations from the computerized search were bound together with reference lists supplied by various participants to make up a bibliographic listing including over 430 citations. From this listing, articles and abstracts to be procured for review were chosen. Various participants and experts inspected the listing and chose citations they regarded to be pertinent to the downhole project. The selections were transmitted to the Alberta Research Council which administered the procurement of the papers or the abstracts of the paper or conference proceeding when the paper was not readily available. One hundred and thirty seven papers were reviewed by the participants and authors.

4. GEOPHYSICAL INSTRUMENTATION

4.1 Introduction

In this chapter the characteristics, capabilities and suitability of geophysical logging techniques are discussed. Commercially available equipment has been listed in Appendix 3.

Methods are assessed on the basis of the type of geotechnical or hydrogeological information that they can provide. Broadly speaking, borehole geophysical methods provide the following types of information relevant to this project:

mapping fracture zones;
the dip and strike of these fractures;
salinity of borehole fluid;
direction of fluid flow within boreholes;
estimate of moisture content;
estimates of the porosity;
estimates of the dynamic moduli;
estimate of the density;
and mapping lithologies.

Most measurements are effective for a very limited distance, usually only a few centimetres, beyond the wall of the hole. However some methods extend to several metres or tens of metres. In addition, crosshole measurements when combined with the powerful tomographic processing methods, can provide interpretive sections between holes that may be up to, or more than, a few hundred metres apart.

Usually geophysical logging is carried out in uncased holes which are filled with water. However in the case of overburden investigations, the possibility of cased holes should also be considered. Any metallic casing is unacceptable for electrical logging. It is recommended that in this situation perforated PVC casing be used, and that it be allowed to stand long enough for the groundwater inside the casing to reach equilibrium with the groundwater in the

natural formation. Similar considerations would apply to thermal logging, however it should be noted that fairly lengthy equilibrium periods are needed for the thermal method. The nuclear methods are the least susceptible to the effects of casing. It is possible to conduct seismic logging through casing, however it is recommended that every situation be assessed individually. Caliper, television and acoustic televiewer logging is not possible in cased holes.

4.2 Electrical Methods

Eleven electrical methods are listed in Appendix 3. Of these, six appear to have potential for determining the desired parameter. These six methods are: single point resistance, normal resistivity (40 and 80 cm spacing), focussed normal resistivity, spontaneous potential, fluid resistivity, and radar.

In the single point resistance method the measured parameter is essentially the contact resistance of a moving downhole electrode. This log provides qualitative information and has been found useful for locating fracture zones and for giving some indication of the fluid conductivity and therefore the salinity of the borehole fluid. The normal resistivity logs, having a different working configuration than the single-point resistance logs, provide quantitative results. Resistivity being an intrinsic property of earth material and its saturating fluids can also be used to map changes in lithology. The focussed resistivity is a specialized variety of resistivity log which has a greater penetration into the wall rock, and a greater capability to resolve thin beds. The usefulness of spontaneous potential logs is questionable but can be included in the package because it usually forms an adjunct to the resistivity logs. Fluid resistivity logs, which measure the resistivity of the borehole fluid, have been found useful for locating the interface between fresh and saline water (Soonawala, 1983). This can indirectly indicate the points where groundwater either flows into or out of a hole. Similar information can also be provided by high-resolution temperature logs.

A dipmeter is a variation of focussed resistivity logs. The dip measurements are made by correlating the log responses from three or four micro resistivity pads equally spaced about the long axis of the proble. The proble also includes borehole orientation devices to enable calculation of the true dip and

strike of the various contacts in the borehole.

The above-noted electrical tools (except radar) are readily available commercially. Usually the resistivity, single point resistance and spontaneous potential probes are included in one tool, while the fluid resistivity is packaged with the temperature sensor.

Downhole radar is still in the development stages, and equipment is not as readily available on a commercial basis. It is a powerful technique that can sense to at least several tens of metres beyond the hole. It can be particularly useful when the requirement is to detect fractures that do not intersect the hole. Computerized data acquisition and data processing are necessary for borehole radar surveys. Tomographic interpretation has recently been applied to crosshole radar data (Olsson et al., 1986).

4.3 Nuclear Methods

The natural gamma, density (gamma-gamma) and porosity (neutron) methods are considered here.

Natural Gamma: The natural gamma logs can be very useful in differentiating between different lithological units, since these units often have characteristic and distinct potassium, uranium and thorium content. This method can occasionally be used to detect fractures in a borehole. In the spectral gamma method, it is posssible to get an estimate of the quantity of individual radio active elements, the major ones being potassium-40, uranium-235 and -238 and thorium - 232. A suitably large sensor should be obtained if spectral gamma logging is to be successful.

Density: The gamma-gamma density tool is used for determination of material density. This tool measures the backscatter of gamma radiation from a source in the tool. The amount of backscatter is directly related to electron density which for most geologic structures is proportional to the material density. Careful calibration of the tool and caliper information for the borehole is required for reliable evaluation of formation densities.

Porosity: Porosity (neutron-neutron) logs indicate the amount of moisture and therefore porosity assuming full saturation in the rock in the wall of a borehole. They are also good indicators of fracture zones because there usually is an accumulation of water in fractures. However it is possible that concentrations of certain minerals may also cause a response on these logs. It has been reported that a good correlation also exists between the neutron-neutron log response and the point-load strength of rock (Elkington et al., 1982).

4.4 Acoustic Methods

Acoustic methods are usually applied only in consolidated rocks and require fluid-filled boreholes.

Sonic: In this method the transit time (and thus the velocity) and amplitudes of compressional (P) and shear (S) waves are measured. In the simpler type of equipment, which is commonly available commercially, only the first arrivals are detected and this precludes the detection of shear waves. This tool is useful for detecting fracture zones, porosity and rock type. In the more advanced type of sonic logging, the full waveform is recorded at each sampling point in the hole. The P and S wave velocities, in combination with density data, can be used to calculate the dynamic moduli that can provide an indication of the strength of the rock. Paillet and Hess (1986) have provided examples of how the frequency spectrum of acoustic waves can vary with the rock type. A critical consideration is the separation between the transmitter and the receivers. Generally, larger separations would provide data that are more representative of the formation being investigated.

Tube-Waves: Tube-wave logging (Huang and Hunter, 1984) is a surface to downhole seismic method, that also can be referred to as vertical seismic profiling (VSP). It can be used for fracture zone detection, and a correlation has been noted between tube-wave amplitudes and hydraulic conductivity of fractures. The tube-wave logs can also be generated from full waveform logs by appropriate processes (Keys, 1987).

Crosshole Seismic: The crosshole seismic technique, when used with tomographic data processing, can produce a map of the fracture zones in the section between two holes (Wong et al.,1987). In good quality rock the distance between boreholes can be up to a couple of hundred metres, but it should be noted that this range is highly dependent on the quality of the rock. Sophisticated software packages are available for the various tomographic processes which have been developed.

Crosshole seismic surveys can also be carried out using in-hole shear hammer sources. P and S wave analysis can be carried out to calculate the dynamic moduli of the intervening rock mass. Tomographic inversion is not possible with the limited number of ray-paths that can be generated in such a system.

4.5 Caliper Logging

Caliper logging is an essential component of any logging program. In this tool, mechanical arms are used to measure the diameter of a borehole. Caliper information has the following uses: fracture zones can be mapped; borehole diameter is used to correct and calibrate other tools; and some idea of the lithology can be obtained since the hole diameter in softer rocks tends to be larger than in more competent rocks.

4.6 Thermal and Flow Logging

Thermal logging has been used to determine the points where water flows into or out of a hole, and the direction of flow. Therefore, it can be of use in hydrogeological investigations. The natural thermal gradient can also be determined with this method. Drury (1984) has provided an analysis describing how fluid flow directions can be determined from thermal logging.

The heat-pulse flowmeter has been used to determine very slow-velocity movement of borehole fluid (Hess, 1986). It is claimed that velocities that can be determined are an order of magnitude lower than those detectable by impeller type flowmeters. The impulse or impeller type flowmeter serves the same purpose as the heat-pulse flowmeter but, as noted earlier, is far less sensitive.

4.7 Television and Acoustic Televiewer

The television and acoustic televiewer logs are used to locate fracture zones along boreholes with an accuracy of the order of millimetres. By analyzing the shape of the image, the dip and strike of the structure and fractures can be calculated (Lau, 1980). Therefore, these methods can be useful for detailed geotechnical studies, where the dip and strike information can be useful for interpolating fracture zones in rock between boreholes. The working principles of the two methods are different, but similar results are obtained. In order to use the television technique, it is necessary to have clear borehole fluid, and preferably light-coloured rocks.

5. REVIEW OF GEOTECHNICAL APPLICATIONS

5.1 Purpose of Review

This chapter summarizes selected papers which focus on geotechnical applications of geophysical logs. The selected papers concentrate on those studies which had positive results.

Of particular interest are tool developments which have taken place in the metallic mineral sector and the oil and gas sector and which have not been applied in coal or oil sands. Both qualitative as well as quantitative studies have been included in the review.

A one page summary form for each reviewed paper is included in the report appendices.

5.2 Geotechnical Parameters and Investigation Methods

5.2.1 Geotechnical Parameters of Interest

Geotechnical parameters required in the design of mine and tailings facilities are listed in Table 1 (Section 2.1).

This review has identified a number of borehole geophysical techniques which have been utilized to measure some of these parameters.

5.2.2 Investigation Methods

The general categories of geotechnical investigation methods are illustrated in the flow chart in Figure 2. The flow chart places borehole geophysics in its proper perspective, both in its currently accepted application and potential use. In evaluating and eventually choosing any given geophysical method, the technical merits and cost effectiveness of the method must be evaluated. In addition, the suite of methods which are eventually selected for testing should be done so that they are complementary and consistent with each other as well as the standard in-situ geotechnical tests.

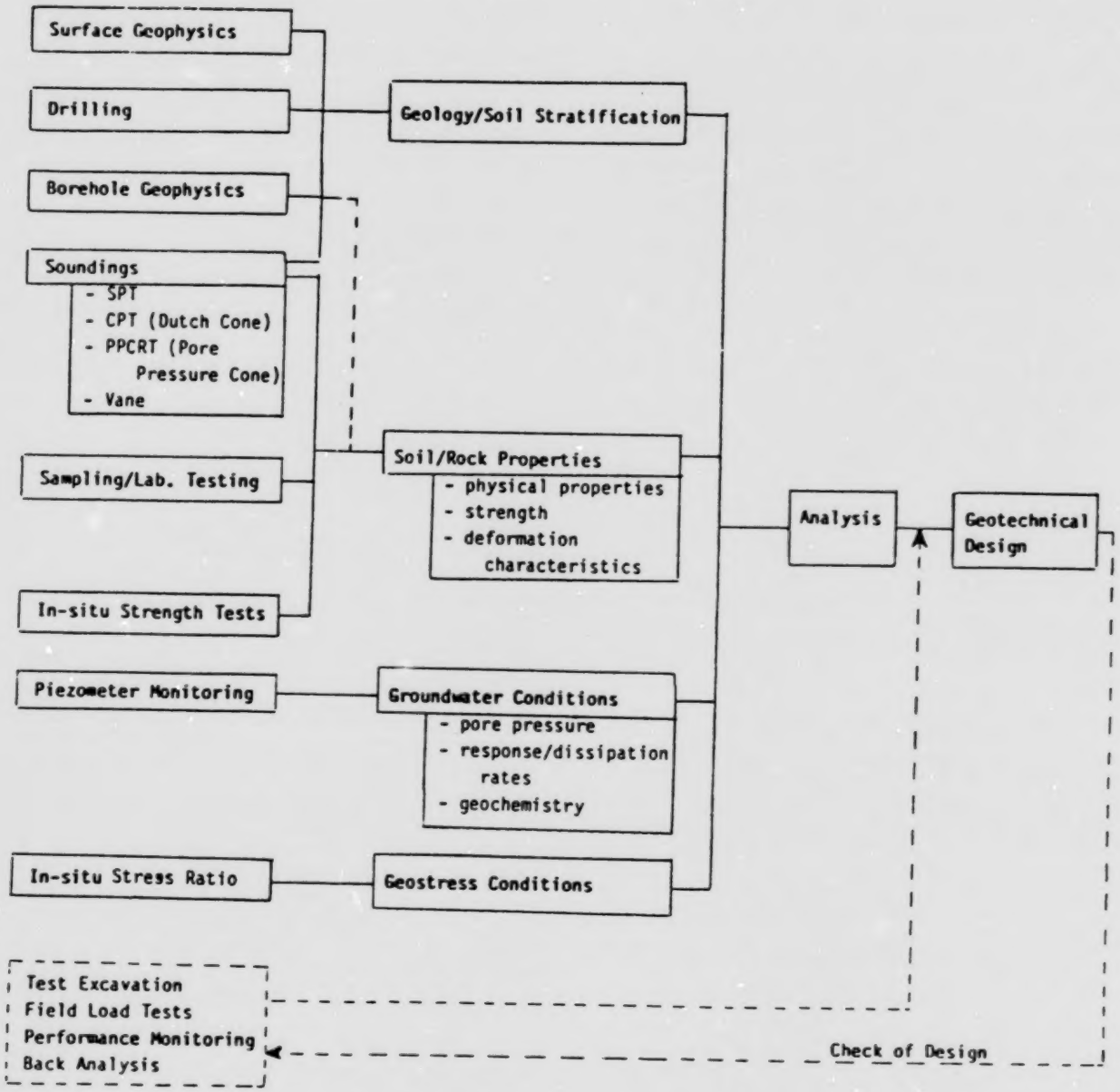

Figure 2 : General Geotechnical Investigation Methods and Objectives.

5.2.3 Evaluation of Methods

As recently mentioned by Tavenas, (1987) in-situ test procedures, should meet the following criteria:

- must be reproducible,
- calibrated against other tests,
- calibrated against performance.

Additional desirable qualities may be:

- simplicity,
- economy,
- good simulation of the problem.

These yardsticks have been utilized to evaluate the geophysical methods discussed in this chapter.

5.3 Summary of Relevant Papers

5.3.1 Borehole Televiewer

The borehole televiewer is an acoustic based probe which is available through at least two companies. This tool produces an image of the open wellbore to delineate such features as fractures, bedding planes and open porosity (Vuggy) conditions. The images which are recorded are the variable density representation of reflected acoustic waves. The reflected acoustic wave energy is dependent upon rock reflectance, wall roughness, wellbore fluid attenuation and hole geometry.

5.3.2 Testing and Calibration of Downhole Probes

One paper (Bernius, 1981) reports on a standard borehole test site in Ottawa and a second (Wenk & Dickenson, 1981) reports on a calibration facility in South Australia. The Ottawa site consists of four holes for which detailed geological logs and core are available to relate to physical property data acquired by logging. The Australian facility has been established to correlate gamma tool readings to equivalent U_3O_8 grades. Additional calibration facilities also exist in several U.S. centres.

A third paper (Mathew, no date) discusses high resolution core density logging ("Coran" instrument) which is based on gamma ray attenuation by core. It may be useful to compare field density results with data from this type of instrument in terms of cost effectiveness.

Development and use of standard calibration facilities will result in more uniform and universal logs and "absolute" property data.

5.3.3 Borehole Radar

At least two systems have reached the proto-type and testing stages. One system operates in the lower frequency range (< 50 MHz) while a second system (VHF) operates in the 30 to 300 MHz range. These systems have been tested in actual or simulated field conditions in both single and cross-hole configurations. Detection distances range from approximately 10 to 100 meters. The systems are dependent upon rock masses having a high resistivity and a large resistivity contrast to identify targets and may not be applicable in poorly consolidated sediments.

In a geotechnical application, the useful targets would be major fractures that offer a resistivity contrast for detection. This contrast may be caused by water saturation of the fracture.

5.3.4 Holography

Holography may be considered to be a geophysical procedure. A single paper (Bass et al., 1986) describes a new instrument for measuring the in-situ level of stress in boreholes. The instrument operates on the principle of locally relieving the stresses acting in a rock mass by drilling a small hole into the borehole wall and recording the resultant displacement field by holographic interferometry. A large diameter hole (> 30 cm) is required. The technique is experimental and as a result of the large hole diameter, expensive. For these reasons it may not be worthy of further consideration.

5.3.5 Dipmeter

The dipmeter has been widely applied in oil sand reserve evaluation and highwall stability over the past 10 years. Development of software and tests to compare dipmeter plots against oriented core data have taken this method to a high level of reliability. Bedding and local erosional surface features have been the primary strike/dip targets in these surveys. Resolutions as small as 5 mm have been reported (C. Brawner, 1987).

Bedding dips and geologic structures are key parameters in open pit slope stability evaluations as well as in underground mine design. Consequently dipmeter logs should also be directly applicable to foothills and mountain coal deposits and to tailings foundation studies.

Several papers have been located which accent the interpretation procedures required to fully evaluate dipmeter plots. One paper by Babcock, (1978), extends dipmeter interpretation procedures to identifying steeply dipping fractures intersected by a borehole. The method utilizes measurement of the azimuth of hole cross section elongation at zones of overbreak where the drill bit has encountered a fracture. Data are obtained from the caliper part of the dipmeter log. Satisfactory results have been obtained from numerous formations in Alberta. It can be particularly useful for identifying those fractures which do not have a significant resistivity contrast, and hence are not identified on the dipmeter plot.

5.3.6 Combination Probes

The complementary nature of some of the geophysical probes provides the basis for deriving rock mass characterization from integrated studies. In coal reserve evaluation studies the usual log suite includes the following probes: caliper, natural gamma, gamma-gamma (of various spacings for density), neutron - neutron or neutron - gamma, resistivity and sonic. In oil sand evaluation studies the usual log suite includes the following probes: caliper, natural gamma, gamma - gamma, neutron - neutron, resistivity or induction and SP. From these geophysical log suites, programs for both oil sands and coal have been developed to generate physical characterization data including density, porosity, saturation as well as oil

sand and coal quality parameters. However very little work appears to have been done to obtain data at a similar level from the overburden materials associated with coal and oil sand deposits.

Geona Enterprises Ltd. of Calgary has developed a statistically based computer system of log analysis and detailed reservoir mapping for heavy oil and oil sand applications, using the standard suite of logs. The system produces measurements of lithofacies gradation from clean clay rich shale to clean coarse sand. The data from all geophysical logs is systematically combined to produce the lithological discriminations. Currently proven and potential physical parameters that can be derived from this method of log analysis include: moisture content, including adsorbed water, gas content, degree and type of cementation, grain size distribution, clay mineralogy and plasticity. Since the system is statistical it requires a large data base.

A paper by Dyck and Young, (1985), urges that rock characterization for a variety of purposes including geotechnical properties, should be pursued by combining geotomography procedures using magnetic, electromagnetic and seismic measurements.

5.3.7 Sonic, Tube Wave (VSP), Acoustic and Geotomographic Methods

A large number of papers characterize rock and soil properties from measurement of compressional and shear wave propagation behaviour. These waveform borehole methods may be broadly categorized as:

a) Conventional borehole acoustic transit-time logging;

b) Borehole acoustic - refraction waveform logging;

c) Acoustic borehole televiewer imaging of the borehole wall;

d) Surface to borehole seismic investigations tube waves (VSP) with very long seismic wave lengths;

e) Cross-hole seismic logging.

Conventional acoustic-logging systems use frequencies of 10 to 25 KHz and source-receiver spacings of 0.3 to several meters to measure compressional velocity of material around the borehole. Some systems will also provide S-wave travel times.

Waveform logging techniques involve the digital recording of the entire acoustic pressure signal received by a conventional acoustic logging probe. The acoustic waveform has been used to determine the in-situ properties of fractured rocks and other geohydraulic parameters.

Tube-wave (Vertical Seismic Profiling) operates with surface shot points and down hole compressional wave recording. Positioning and orientation of the shot point allow three dimensional rock characterization, including acoustic detectable features not intersected by the borehole.

One abstract presents the status of an acoustic logging tool known as "EVA" (Arditty, et al.). The tool, together with a data support system, collects and processes data to provide P, S and Stonely waves, velocity logs, amplitude logs and period logs. It also establishes the different elastic parameters. Further iso-offset section and data processing results in lithology identification, casing cementation requirements, damage zone identification and fine lithologic changes. It may also be used to estimate fracture permeabilities but the paper abstract available does not provide details on the method.

Cross-hole seismic logging allows the determination of rock/soil properties between boreholes and has formed the primary data source for geotomography. This procedure has been applied to identification of fracture zones, density distribution and mapping lithological contact surfaces.

Generally, the foregoing acoustic tools have been used for directly deriving dynamic elastic properties including: Young's modulus, shear modulus, bulk modulus, Lame's constant and Poisson's ratio. In addition the methods have been employed to identify major fractures, fracture zones, and lithological surfaces. Various studies (New, 1986; Poule, 1984; Paillet, 1985; Elkington et al., 1982; and others) have been done to illustrate the direct correlation of

geotechnical properties to sonic/seismic data. Geotechnical factors examined include such parameters as rock quality designation (RQD), bucketwheel diggability, unconfined compressive strength and porosity.

In summary, adequate evidence exists to show that sonic property data including wave velocities, attenuation factors and full wave form characteristics may be used to derive relevant geotechnical data for mine and tailings planning purposes.

5.3.8 Gravity Probes

Several papers describe the application of gravimeter surveys to mining. The borehole gravimeter has an investigation range of several hundred meters and this is its singular advantage over most other borehole methods. However, the primary mining application is its ability to identify relatively large bodies which possess a measurable density difference (contrast) in comparison to the surrounding rock. Specific geotechnical data from gravity surveys have not been presented in the literature reviewed.

5.3.9 Neutron - Neutron Probes

This probe comprises a fast neutron source and a slow neutron detector. Published work (Halker et al., 1982) by the U.K. National Coal Board has demonstrated a close correlation between a Fracture Index derived from core logging and the neutron log. The Fracture Index was also correlated to the sonic log derived data and a caliper log. However, of the three logs, the neutron - neutron logs consistently showed the best correlation with the Fracture Index when water saturation or clay filled. Reasonable results were also obtained in generating compressive strength correlations with a related parameter, the Hydrogen Index. From the correlation a synthetic (continuous) unconfined compressive strength log was derived. A similar exercise was repeated in another paper to show the relationship between Neutron -Neutron log responses and point load strength data. Here again, the correlation was superior to other commonly used logs including the sonic log data.

5.3.10 Gamma - Gamma Density

The gamma - gamma density probe has a long history of use in both oil sands and coal logging suites. This tool provides bulk density values which are absolute values when the tool is properly calibrated. The results however are sensitive to borehole conditions, particularly the borehole diameter, and must be corrected for diameter variations. Most logging systems can make this correction automatically over a small range of diameters. Recent geotechnical applications include the use of measured density values to estimate liquefaction potential in foundation areas where saturated loose sands are known to exist. In one study the method of Seed and Idriss (1971) using relative densities derived from log data are compared favourably to standard penetration test (SPT) data. A similar favorable comparison was made by calculating void ratios from log data and estimating liquefaction potential using the critical void ratio concept (Wilder et al., 1983). The geophysical log method has the advantage of identifying thin zones of low density. However, it suffers from its dependence on borehole conditions and shallow penetration (ie. small sampling radius which may correspond to the zone of borehole disturbance).

A second procedure, developed in Holland (Nieuwenhuis & Ruijgrok, 1978) utilizes separate gamma source and detector sets in separate boreholes, (i.e. a cross-hole gamma system). The purpose of the method is to provide densities for layers not less than 15 cm. The equipment and procedure were designed to provide reliable in-situ densities for a variety of structures such as hydraulic fill, tailings compacted fill and densified hydraulic fill. The disadvantages of the method include dependence upon accurate positioning and orientation of the adjacent boreholes and borehole disturbance.

A third application (Timofeev et al., 1972) of gamma - gamma density logging demonstrates a correlation between log determined densities and rock bolt efficiency. Correlations of strain changes and pressure changes to density logs were also completed in this study.

5.4 Results

Based on the literature search, those methods which offer the best promise for application to either coal or oil sand mining operations or both include:

a) Acoustic Televiewer

This procedure offers a complete rendition of the acoustic reflectivity of the borehole wall and has potential application in fracture identification and providing an alternate method for providing detailed logs where core recoveries are unsatisfactory. The method merits further study.

b) Pulse Radar

The radar method would appear to have some application where fracture identification is merited. Penetration distances are quite variable and highly dependent on local resistivities. Given the resistivity contrast, the radar method may also have an application in defining other structural features that are relevant to geotechnical design e.g. overburden glaciotectonic structures.

c) Dipmeter

The dipmeter survey has direct application in slope stability evaluations and slope design for both coal and oil sand mining. Moreover, the examination of the application of this method to coal reserve evaluation, especially foothills and mountain coals, is definitely warranted. Babcock's method also appears to have merit for identification of fractures and fracture patterns.

d) Combination Probes

Geophysical probes in various combinations offer promise of providing useable data to define such geotechnical parameters as grain size, moisture, porosity, and plasticity. The best avenues for further study are software development and correlation analyses.

e) Sonic and Seismic

Geotomography to identify geologic structure and other properties such as in-situ density merits further study for overburden evaluation and tailings investigations. Methods for computing elastic parameters are quite well established in the literature particularly from conventional sonic borehole probe data.

f) Neutron - Neutron

The neutron - neutron log has seen successful application in British coal fields as a correlatable tool with point load test data and unconfined compression data. Further investigation to ascertain its possible application in Canadian coal and oil sand evaluation should be explored.

g) Gamma - Gamma

Cross-borehole tests to measure in-situ densities very accurately have had some measure of success in Europe. Application of this method to tailings liquifaction studies has distinct possibilities. Further study should be considered.

5.5 Conclusions

The relative importance of various geotechnical parameters depends on site specific conditions and the type of mine or facility likely to be designed. Generally, the parameters which are of greatest interest include density, moisture, porosity, saturation, shear strengths (effective and undrained) and structural features. Interpretation of structural features is also very important.

The available literature demonstrates that several borehole geophysical probes and methods as discussed have been sufficiently well developed to warrant testing in the coal and/or oil sand environment in a systematic manner.

6. REVIEW OF HYDROGEOLOGICAL APPLICATIONS

6.1 Introduction

The hydrogeological component of this project is focussed on the application of downhole geophysics to the determination or potential determination of major hydrogeologic parameters. The following major parameters have been identified, and in descending order of importance are:

(1) permeability
(2) pressure head or pore pressure
(3) porosity, storativity (confined aquifers) and specific yield (unconfined aquifer)
(4) moisture content and water quality in the unsaturated zone

These parameters apply in unconsolidated and consolidated sediments.

The papers identified and selected in the literature search plus any additional references in the hands of the authors were reviewed. Many of the most recent papers are related to unique site conditions and information needs particularly for igneous-metamorphic geological settings. Whether or not these techniques can be extrapolated to the sedimentary environment with success has not been examined.

6.2 Current Uses

6.2.1 Borehole Damage and Drilling Effects

Nearly all log interpretation in the petroleum industry is conducted under open hole conditions. As a result, tool design and log interpretation procedures are geared toward removing or correcting borehole effects due to mud invasion and the drilling process. To maintain hole stability, it is "mudded up" to ensure that the weight of the drilling fluid column is greater than the pressure of the fluids in the formation. While this achieves mechanical stability of the hole by applying a backpressure to the formation, it also forces the drilling fluid to enter the formation.

In shallow fresh water environments, it is questionable how much mud invasion actually takes place. Alger (1966) contends that mud invasion is limited because the porosity is high and the pressure differential between borehole and formation fluids is relatively low. In most cases, therefore, the resistivity value from a 41 cm short normal electric curve is very close to the true formation resistivity. However, Dyck et al. (1972) has observed that invasion of drilling mud does occur in shallow, fresh water environments sufficiently to cause errors in the 41 cm normal resistivity log. A small diameter induction probe recently developed by Geonics Ltd. may prove useful in accurately measuring conductivity beyond the mud invaded zone.

If the 41 cm short normal electric log reflects true formation resistivity because of limited invasion as stated by Alger (1966), then the effects of mud resistivity are insignificant. The log interpretation procedure is then simplified where mud rotary drilling is the predominant method.

The aspects of mud properties and formation damage in shallow groundwater wells was extensively reviewed by Haines & Emerson (1972). In contrast to the specifically prepared and often exotic mud mixtures employed in petroleum drilling, that used in water well drilling often consists of a simple mixture of bentonite and locally available water. The formation of a mud cake is perhaps the most important function of the mud in drilling technology. The mud cake both stabilizes the borehole walls and reduces fluid loss to the formation. The thickness of the mud cake depends primarily on the rate of deposition of solids from the mud, the rate of erosion by the circulating mud, the strength of the mud cake, the temperature and the differential pressure between mud column and formation.

The use of deep penetrating side wall tools in the coal and oil sands formations significantly reduces any effects of mud caking or invasion.

6.2.2 Permeability (primary and secondary)

From Resistivity Logs

The determination of intergranular permeability is based on extensive log experience developed within the petroleum industry. The groundwater industry has generally adopted, without modification, the well documented Archie formula, F = Ro/Rw where F is the formation factor, Ro is the saturated resistivity of the formation and Rw is the resistivity of the formation pore water. The Archie formula, derived for hydrocarbon applications, is only applicable in saline water environments where current flow is through the formation fluid. Under this circumstance F is a constant for each lithologic unit. In fresh water environments, most water bearing aquifers contain some clay which results in both a surface conduction and pore fluid current flow. The net effect is that the formation factor is no longer a constant but rather varies with Rw (Alger, 1966; Worthington, 1975).

A number of approaches have been developed to determine either F or Rw. Jones & Buford (1951) solve the equation by determining F from laboratory studies and Ro from an electric log. Kwader (1982) determines Rw from a fluid resistivity log or from a knowledge of groundwater quality determined on near-by pumped wells. Another approach is to determine Rw by cross-plotting Ro versus porosity obtained from a neutron or density log. Rw can be measured directly in the borehole using a fluid resistivity tool. However, this approach necessitates developing the well to remove all foreign water and mud that accumulated during drilling. A fourth approach is to correct F or Rw by a parameter indicative of clay content. The ultimate objective being to determine F where a relationship between F and permeability is proven to exist (Croft, 1971; Kwader, 1982). F can also be determined from $F = a/\phi^m$ where a is usually 1 and the cementation exponent m = 1.3 to 2, depending on lithology. ϕ (porosity) can be obtaining from neutron, gamma-gamma on acoustic velocity logs (Keys, 1987).

Because of the effects of surface conductance in fresh water environments, the outstanding problem in quantitative hydrogeological applications is the field determination of Rw. Worthington (1975) has identified the induced polarization method as a possible technique to define clay content and hence correct for surface conductance effects.

A quantitative assessment of the hydraulic conductivity of near surface materials at a dam site was developed by Schimschal (1981). He used hydraulic conductivity measurements calculated from pump tests, porosity measurements from core samples and water quality measurements from water samples to relate the hydraulic conductivity to the resistivity log. The formula:

$$\log Ro - \log Rw + \frac{m}{D} (A\, k^{-B} - C)$$

was developed from the following equations.

$$N = A\, k\text{-}B \qquad (1)$$

$$N = C - D \log \phi \qquad (2)$$

$$Ro/Rw = \phi^{-m} \qquad (3)$$

where N = neutron response, k = hydraulic, ϕ = porosity

m = cementation exponent, Ro = bulk resistivity,

Rw = pore fluid resistivity and A, B, C, D are constants.

Constants A and B are calculated from equation (1) by plotting k from pump tests against neutron log response. C and D are found from plotting porosity determined from core samples against neutron log response. Rw is determined from water samples and m is calculated from equation (3) by plotting ϕ against Ro.

There appears to have been significant progress made in the oil industry for defining log derived permeability. Examples include:

1. Dependence of "k" on water saturation which assumes that residual (is reducable) water saturation (S_w) is proportional to specific surface area. Timus (1968) tested the relationship on sandstone with the equation,

$$k = \frac{a\,\phi^{b}}{S_w^2}$$

2. Cheng (1986) has a modified version by incorporating a porosity correction factor F into the Timus equation. In his particular application the best calibration was obtained by the eg.,

$$k = 0.136\ \frac{(\phi + F\phi)^{4.4}}{S_w^2} \qquad \text{(Timus Equation)}$$

and

$$k = C^2\ \frac{(\phi/100)^6}{(S_w/100)^3} \qquad \text{(Wylie - Rose Equation)}$$

k = permeability
ϕ = effective porosity (%)
F = porosity correction factor (dimension not applicable)
Sw = irreducible water saturation (%)
a+c= fluid dependent constants

These relationships are unique for each site and the solution for the above formulae can only be trusted if these relationships are strong. In the sedimentary geology of the Alberta plains, these relationships may be nonexistent. However, the approach shown here may work for different and more complex suites of logs and warrants further investigation.

From Gamma Ray Logs

Kwader (1982) has demonstrated a correlation between the "average" natural gamma activity of a hydrogeological zone and its formation factor. This approach is based on the assumption that either only one type of clay is present throughout the sequence or that the clay ratio responsible for gamma activity is constant.

As early as 1963 (Patten & Bennett) had indicated an interrelationship between gamma radiation and formation factor. Sandstones of high porosity are indicated by low formation factors and low radiation intensities. Sandstones that are lower in porosity because of high clay content will be indicated by low formation factors and high radiation intensities. Sandstones that are lower in porosity because of other causes will be indicated by high formation factors and low radiation intensities. Therefore, it should be possible to estimate the relative effectiveness of sandstone aquifers by comparing their formation factor and gamma ray data. This concept is supported by Rabe (1957) and Gaur & Singh (1965). Rabe established a relationship between permeability and gamma radiation for clay bonded Cretaceous sands of the Denver-Julesberg Basin. The relationship is limited to clay bonded sands as calcareous or siliceous cementing materials, which reduce permeability, would not be expected to increase gamma radiation above the clay free line. Gaur & Singh established a permeability relationship with the area under the gamma curve for an Oligocene sand. Oil sand acquifers are incremental sands which may not necessarily have any clay minerals. Their permeability is a function of grain size distribution.

A linear response between gamma radiation and clay content was established by Heslop (1974), and Johnson & Linke (1977) successfully correlated cation exchange capacity (CEC) with gamma response for sandstones in the Mackenzie Delta. Wheatcraft et al. (1986) likewise propose the use of CEC data based on gamma response, not specifically for a permeability determination but rather to characterize sediments for pollutant attenuation.

The utilization of gamma radiation to quantify permeability seems to have met with both success and failure depending upon the types and amount of clay assemblage, and the degree of cementation other than clay bonding. Because the gamma log is a commonly run log, a good potential exists for its utilization in determining permeability directly under given geological conditions, or as a means to correct formation factor or Rw.

The corrections to the Archie equation for clay content assume a consistent geochemistry and content of the clay. This may not be a valid assumption for the Plains sedimentary geology. What is needed is a detailed model of radioactive isotope content of the various clays. Hydrogeologic investigations

using resistivity logs and Archie's equation will be at best a purely empirical correlation. The model on which Archie's law was developed involves Poiseville's flow in granular medium and is not valid for the geochemical structure of clay materials.

Gamma spectral logging or spectroscopy of neutron-induced γ (Hearst and Nelson, 1985) can provide qualitative information of the types of clays or minerals which emit γ-rays. The qualitative spectral signature for each type of clay and mineral must be identified to allow the calibrated tool to diagnose materials encountered in the borehole. A quantitative analysis of the materials is more difficult using this technique.

From Flowmeters

Development of geothermal reservoirs and site investigations related to radioactive waste disposal has resulted in a concerted effort to use flowmeters to measure water flow (Schimschal, 1981; Syms, 1980, 1982; Hess, 1982, 1984). The major thrust in the development of this technique has occurred within moderately deep test holes within an igneous-metamorphic geologic setting where resistivity exceeds thousands of ohm-meters and is often difficult to interpret (Keys, 1979). Flowmeter determination of permeability was developed as an alternative to the calculation of formation factor from electric logs.

Flowmeter surveys are run either within cased holes which have been perforated or screened or within open holes requiring a correction for borehole roughness with a caliper log. Because of the depth of hole associated with geothermal reservoirs and radioactive waste disposal sitings, a multiaquifer setting with internal flow is common. However, this is not always the case for shallow holes within the sedimentary environment. Within the igneous-metamorphic geologic setting, the holes are normally in good quality rock that does not require dense drilling fluids to maintain the opening and therefore mud invasion is not a problem. Within sedimentary environments, where holes are often drilled with mud because of hole stability problems, there is a need to flush and develop the hole prior to running a flowmeter survey.

In shallow sedimentary environments, there is rarely any significant hydraulic differential between the borehole and formation fluid.

Therefore, effective flowmeter results can not be expected from measurements of only natural vertical flow in a borehole whose water level is at equilibrium (Manabe et al., 1983). That is, internal flow or "thieving" must be occurring in order for the flowmeter to respond. An effective analysis of water motion can, therefore, only be accomplished by changing the water level in the borehole through a pump-in or pump-out test in order to induce hydrodynamic flow.

The distribution of permeability within a borehole can be analyzed in one day using a flowmeter. Flowmeters can be added to any logger at a relatively low cost and they are standard with many commercial logging companies. A heat pulse horizontal flowmeter capable of measuring seepage rates between 0.02 and 3m/day (0.1 and 10 ft/day) was tested in the laboratory (Melville et al. 1985). Very small channelization around slotted pipe and hydraulic conductivity contrasts can invalidate instrument response; therefore wells must be constructed and probes placed with great care.

An experiment comparing flowmeter analysis to tracer travel time and wellbore dilution is currently underway near Mobile, Alabama. The results from this study will indicate effectiveness of the flowmeter and provide suggestions for field procedures.

Other applications of flowmeters could include:

1. Constructing flow nets for tailings dyke seepage evaluation for environmental monitoring or filter performance.
2. Definition of barriers to water flow in groundwater modelling.
3. Dewatering/depressurisation efficiency measurement.

6.2.3 Pressure Head/Pore Pressure

Manabe et al. (1983) appears to be the only paper which addresses the issue of water head distribution for multi-permeable zones within a single borehole. Their method is based upon use of the flowmeter in conjunction with pump-in or pump-out tests. It is questionable whether or not this approach would have universal application to exploration drilling programs in coal or oil sands.

6.2.4 Porosity/Storativity/Specific Yield

Within the petroleum industry, porosity has traditionally been derived from the porosity suite of logs - neutron, density and sonic, with neutron and density generating a total porosity value. Porosity can be calculated directly from the density log with a knowledge of grain density and fluid density. Neutron logs, on the other hand, are calibrated directly in limestone porosity units or must be calibrated through core or laboratory studies in other rock types.

Porosity is very important to calculating hydrocarbon saturation in the petroleum industry. In groundwater studies, determination of porosity is not as important, because the variations in porosity are usually small for fresh water aquifers. A specific yield of 0.2 for water table aquifers and a storativity of 5.0×10^{-4} for confined aquifers are reasonable estimates. The influence of grain size and its direct relationship with permeability is of far greater importance.

In addition to the standard petroleum industry porosity logs, other approaches at defining water content within igneous-metamorphic geologic settings have been attempted. These are the electromagnetic propagation (EMP) method for determining water saturation in low porosity rocks and the nuclear magnetic resonance (NMR) method for distinguishing between bound and free water associated with clays and hydrothermal alteration products (Nelson, 1982). Tools using these methods are not readily available.

Secondary porosity can not be easily measured. To date, only the flowmeter appears to have been successful (Tate et al., 1970). Plumb et al. (1985) have attempted a qualitative indication of relative fracture permeability based on attenuation of Stoneley waves. Nelson (1982) commented that reliable determinations of permeability continue to be an elusive goal.

Indirect measures of flow can be obtained from fluid conductivity and temperature logs. Edmonds et al. (1976) used these logs to determine the source of water from water wells by tracing changes in fluid conductivity and temperature to induced flow from a river. Intervals of high secondary porosity can be identified by cross plotting neutron and acoustic velocity logs (Keys, 1986).

6.2.5 Water Quality

Alger (1966), Emerson & Haines (1974) and Kwader (1982, 1984) and others have demonstrated a strong correlation between total dissolved solids (TDS) and water resistivity Rw.

Kwader (1985) measures water quality with geophysical logs by establishing a relationship between water resistivity and ion concentration in the lab and obtaining the water resistivity from cross plots of bulk resistivity and porosity. Again, this method will not work unless a good relationship exists between porosity and resistivity. In sedimentary geology environments, resistivity is likely to be influenced more by changes in clay content, clay geochemistry and lithology, than by changes in fluid resistivity adjusted for porosity.

The small diameter induction probe mentioned in section 6.2.1, appears useful for measuring changes in water quality of an aquifer over time. This tool may prove to be more useful in determining water quality than classical resistivity logs. Temperature and fluid conductivity logs can also indicate water quality and identify flow regimes and flow sources.

6.2.6 Degree of Saturation and Water Quality

Within the unsaturated zone, only the radiometric logs - neutron, density and gamma, have any potential to correlate with formation properties. Neutron logs can be calibrated to define porosity below the water table and moisture content above the water table. Hearst (1979) used neutron logs to establish moisture content profiles in partially saturated alluvial sediments. Carroll & Muller (1973) successfully determined water content, porosity and degree of saturation using only a knowledge of the formation resistivity and density in partially saturated alluvial sediments. Extensive work is being performed at the Nevada Test Site on calibration and correction of neutron logs for determining moisture content above the water table.

The small diameter induction probe (section 6.2.1) at present appears to be the only tool with potential of recording water quality in the unsaturated zone.

6.3 Summary and Conclusions

The literature review has indicated a number of new approaches in downhole geophysical logging techniques. Many of these techniques are specific to particular problems and geologic settings. New tools and methods such as the acoustic borehole televiewer, seismic waveform analysis, and acoustic soundings have already met with some success in the Plains surface mining environment and may become more widely used. Other methods such as nuclear magnetic resonance, electromagnetic induced polarization and microelectric scanning have had some succes. The many cross plotting techniques used in conjunction with Archie's formula extract information from standard logs. Computer analysis, including such techniques as cross-plots, ratios, differences and statistical studies will often reveal relations that are not initially obvious between geophysical properties and hydrogeological parameters.

There is potential for greater use of the flowmeter. A major disadvantage lies in the need to flush the borehole. Great care must be exercised in well installation and probe placement for these instruments to work.

The conventional logging suite comprised of a resistivity, gamma, caliper, density and neutron log, appears to provide the best potential for in situ determination of hydrogeological parameters associated with the Plains sedimentary environments.

A suite of hydrologic logs including the small diameter induction log, temperature log and conductivity log may together provide information on flow and water quality and will also describe the borehole fluid which affects other logs.

7. CURRENT RESEARCH AND DEVELOPMENT

7.1 Research Groups

Leading researchers and organizations were contacted to review the current state-of-the-art with respect to borehole geophysics. It was recognized that this review would identify geophysical probes which had potential for use later in the project.

Discussions with program participants, some of the program reviewers and staff at the Geological Survey of Canada resulted in the preparation of an initial list of both researchers and organizations which are or may be working in the subject area. These researchers and organizations are presented in Appendix 4, A and B and include worldwide groups from the private, education and government sectors. Most of these groups were contacted in this initial survey.

7.2 Interview Method

The personnel and organizations listed in Appendix 4 were interviewed using a structured questionaire. Information pertaining to potentially relevant borehole probes, performance data, other contact references and pertinent literature were requested.

7.3 Measured Parameters

In order to focus the search activity, a specific set of geotechnical and hydrogeological parameters were compiled. The parameters which are normally required in the design of mine and tailing facilities are listed in Tables 1 and 2 in Section 2.1 . Those borehole geophysical methods which show promise in terms of their potential ability to deliver these key parameters to an acceptable level of accuracy are discussed in the following section. This section has been organized on a generic basis.

7.4 Geophysical Probes

7.4.1 Impulse Radar Methods

Two probes have been developed and tested primarily in hard rock applications with reasonable levels of success. One of these systems was developed in the U.S.A. by Sandia National Laboratories and has successfully identified fractures up to a distance of 12 meters. Applications in soft rock or unconsolidated materials have not been attempted. A second system has been developed by Boliden in Sweden. This system is a slim hole dual probe transmitter/receiver system operating with a cross-hole geometry and requires a relatively high background resistivity in order to be effective. It has been tested in hard rock applications only. In low conductivity material, a range of 100 meters has been attained in identifying rock interfaces. Weathered zones have been identified with this tool and water-filled fractures could also probably be identified.

A third system, (Collett, 1987) better than either the Swedish or American systems is the Ekko 3 system developed by A Cubed. The system measures dielectric contrasts and is claimed to have a penetration of up to ½ km in granites. This is a surface prototype but the developers indicate that a borehole version would not be an expensive undertaking. Development time would be required. This apparatus is particularly sensitive to porosity and saturation/fluid conductivity changes. A borehole version may have an application in identifying water filled fractures.

7.4.2 Neutron - Neutron Probe

The National Coal Board in the U.K has developed a tool and correlation data for special applications to coal only for identifying the degree of fracturing. The tool is marketed by Robertson Research. This tool has the ability to measure relative levels of fracturing and to estimate powder factors to achieve optimum fragmentation for both coal and overburden (Young, 1987). This tool may have a particularly useful application in new coal basin development. It may also have an application in future oil sand areas where overburden formations containing cemented beds are prominent.

A second generation large diameter pulse neutron tool is under development at Dresser Atlas. The tool is being built with improved sources to provide better data than currently available tools. Indentification of water inflow points and fluid ratios is also claimed. There has been a change in research workers and additional information was not available but this tool may be worthwhile testing for obtaining porosity and saturation data.

7.4.3 Gamma - Gamma Probe

The Commonwealth Scientific and Industrial Research Organization of Australia (Dr. M. Borsaru) replied to our query with a description of the SIROLOG system. This appears to be the most reliable ash indentification system and may have an application in providing a better resolution of clay mineralogy than existing systems. This system is now commercially available through SIE Geosource.

7.4.4 Cross-Hole Seismic

Substantial progress has been made in the development of cross-hole seismic analysis and geotomography. Most of the available probes are slim line tools and have reached or passed the prototype stage. Most equipment will provide compressional wave velocity, shear wave velocity and full wave form data including amplitude and attenuation coefficients. These data can in turn be used to provide dynamic elastic properties, in-situ densities, fracture densities, fragmentation and powder factors. One of the major advantages of this type of system is its ability to sample large material volumes and avoid borehole disturbance problems especially in soft, unconsolidated or uncemented materials. Several applications exist for this type of equipment in mine overburden investigations to evaluate complex structures in three dimensions. Applications also exist in tailings dyke construction where the determination of in-situ densities and the mapping internal dyke structures is desirable. Research work is still underway in developing software for tomographic interpretation of multi-wavepath models.

In this survey, two researchers in Canada were contacted. Dr. P. Young at Queen's University and Dr. J. Wong of Jodex Ltd. appear to have made the most progress and further follow-up efforts to pursue potential applications are warranted.

7.4.5 Magnetic Susceptibility

Dr. W. Morris has developed a slim line probe (MAGLOG) for measuring the total magnetic field and bulk magnetic susceptibility. There is a slight possibility that this probe could be used to identify major zones of oxidation in those areas where appreciable quantities of magnetic minerals exist (iron oxides and sulphides). Active ground water flow zones could possibly be identified by correlation with areas where these minerals have been oxidized. The system has been tested in the oil sands.

Simplec (George Chapel) has also developed a magnetic susceptibility tool for slim holes.

7.4.6 Radio Imaging Method (RIM)

This method utilizes two slim hole probes in a transmitter-receiver configuration using radio wave signals. Various geometric combinations of receiver transmitter orientations are utilized to collect radio signal paths. The data are computer processed using an axial tomographic analysis package. This system will work in dry or wet boreholes in any orientation and is used to map coal seams, faults, washouts and major fractures. It has been used successfully in a number of boreholes in the U.S.A. and is now being tested in Australia. The system was developed by L. Stolarczyk and is available as a commercial logging service through Stolar. An oil sands application is not immediately foreseen but it may offer a method for 3-D mapping of basal aquifers especially if they contain saline or brackish water.

7.4.7 Borehole to Borehole Electromagnetic Systems

Researchers at the Southwest Research Institute have developed a cross-hole electromagnetic system for operation in vertical slim holes. The system operates

with a VHF pulse transmitter over a pulse spectrum of 0 to 500 MHz. It is claimed that the systems will provide data on cavity detection, geotechnical data (type not specified) and saturation levels. Borehole separations are small, in order of 5 to 20 meters. An interpretation program (software) is not available.

7.4.8 Multi-Probe System

The Southwest Research Institute has also developed a multi-probe system which is referred to as a "Geotechnical Probe System". This system includes seismic (P-wave), resistivity and electromagnetic (30 - 300 MHz) radar probes. They are combined to sound the surrounding rock mass to a radial distance of 15 meters from the borehole's axis. This combination probe is designed to identify lithologic as well as structural anomalies such as clay filled fractures, faults and unconformity surfaces. A data storage and plotting system is included to serve the system. The system has been tested in a hard rock environment only.

7.4.9 Heat Pulse Flowmeter

The USGS (Dr. F. Paillet) has recently developed a heat pulse flowmeter based on the principal of heat loss over repeated time increments. The equipment is in the prototype stage but should be available for testing in our proposed program, if desired. The specifications should be compared with similar flow meters (G.S.C., Geosource, OYO etc.) to assess the most suitable probe for our borehole conditions. Paillet also noted that the USGS has a large library of applications and software literature.

7.4.10 Acoustic Televiewers

J. Zemanke at Mobil Research developed an acoustic televiewer which is now available through Simplec Manufacturing. The acoustic televiewer provides a photo-like image of structural and textural features for the complete borehole wall. It is designed primarily to offer a complete rendition of fractures and bedding planes which intersect the borehole. This tool provides reliable fracture data in other geology and it is recommended that testing be considered in the plains sedimentary environment.

Schlumberger has a probe called the Borehole Televiewer which is also an acoustic logging tool. This probe produces an image of the well bore to delineate fractures, bedding planes, cavities and vugs in open holes. The tool is available in two diameters, 45mm and 95mm.

7.4.11 Dip Meter Probe

This probe is based on a three or four pad resistivity tool. It is not a new tool but over the past 10 years extensive work has been done by Schlumburger and others to develop additional software for interpreting bedding and other planar features. These tools are available in slim line versions from certain contractors.

7.4.12 Formation Microscanner Service

This tool was developed recently by Schlumburger and uses data from a dense array of electric sensors. These micro-electric scanning arrays are set on two caliper pads of a dipmeter tool. The system uses a new technique to make high resolution images of the formations. Two images oriented at right angles to each other are displayed using variable intensity gray scale. Major uses include: identifying fractures, recognizing secondary porosity and defining sedimentary structures. The tool is only available in a large diameter format and the minimum hole diameter is 160 mm. This tool appears to have potential uses in geotechnical investigations, especially in structurally complex areas.

7.4.13 Measurement While Drilling (MWD)

The oil and gas sector has seen the development of several systems to measure certain parameters at the bit while drilling. While most of the measured parameters are mechanical, two geophysical logs, gamma and resistivity, are included in these systems. The system measures and records mechanical and hydraulic drilling data and has been used to promote rig safety, drilling efficiency and on-the-spot preliminary formation evaluation.

7.4.14 Low Frequency EM Probe

Crone Geophysics has developed a pulse EM slim hole tool operating in the 6 to 8 KHz range. While the tool has been developed to map sulphide zones it can be used for identifying conductive clays or pore water with high conductivities. At least one oil sand operator has considered testing the tool for identifying conductive clays. If conductive clays relate to low strength or some other geotechnical property, the tool may be worth testing.

7.4.15 Other Applications

Groundwater Exploration and Research Ltd. (R. Nowak) is using standard tools by OYO, Keck and SIE for developing methods to obtain cation exchange ratios in clay and Atterburg Limits from the standard logging suites. They are also involved in developing a method to measure resistivity in plastic cased holes in unconsolidated sediments.

7.5 Summary

The foregoing methods, probes and systems represent a selection of relevant tools which are either in the prototype stage, have been only recently developed on a commercial basis, or are relatively unknown in coal and oil sands. It is suggested that all of these systems should be given a more critical examination in the second phase of this study. Several cross-borehole techniques, the RIM, fluid flow devices and the scanning devices seem to be potentially useful.

8. SOFTWARE FOR GEOPHYSICAL LOGGING

All modern geophysical logging equipment has digital capability and the field data are stored on either floppy discs or multi-track tape. Therefore it is essential that proper software be available for satisfactory plotting and interpretation of the field data. General inquiries have indicated that though several geophysical logging software packages are available, there is no single specific package that will likely meet all the demands that will be generated by this project (see list below). Therefore it will be necessary to have a mix of publicly-available programs of a general nature, and programs or subroutines developed specifically for this project. The compatibility of the software for the selected equipment (hardware) should be another consideration.

Some of the specific purposes for which software is required are the following: plotting of logs and general data presentation; statistical analysis of data; and special mathematical operations. Additionally, in most systems computer-assisted processing of raw data is necessary in order to obtain the logs.

Statistical processing of data is particularly useful in the case of logs in which there is an inherent scatter in the data, and this includes all nuclear logs and some electrical logs. The simplest statistical treatment consists of the production of histograms, and parameters such as mean, standard deviations and range. Numerous packages for such treatment are available. Cross-plots are also widely used for a visual representation of the degree of correlation between two parameters, calculating the matrix corrected porosity and the structural and geological implications of such correlations. Cross-plot routines are widely available, or can be written in a short time by someone with some programming experience.

To obtain the dynamic moduli of overburden and bedrock material, it will be necessary to perform simple mathematical operations on data involving seismic velocities and density. This is a simple programming task, though automatic picking of events in order to calculate the velocities, is a more formidable task.

Many logging techniques require complex processing of the raw data, e.g. tomographic processing. However such processing would be specific to a system, and would be provided by its supplier.

Since no single specific software package will be completely suitable for this project, the following course of action is recommended. First, the specific operations that are required, e.g. histogram generation, cross-plots, etc., should be identified. Then, it should be determined which software packages available are most suitable for the project objectives. Arrangements should be made to develop the necessary additional or project specific software required.

Following is a partial list of available general log analysis software:

E S Log, Energy Systems Technology, Englewood, Colorado
Log Mate, D and S Petroleum, Calgary, Alberta
Terralog, Terra Sciences, San Ramone, California
PAS System, Petroleum Computing, Dallas, Texas
Log Calc II, Scientific Software, Calgary, Alberta
software, Mt. Sopris, Delta, Colorado
software, Dr. Dusseault, University of Waterloo, Waterloo, Ontario
software, BPB Instruments, Calgary, Alberta
software, GEONA Enterprises, Calgary, Alberta
Logger, Rockware Inc., Denver, Colorado
ELOG, Sinclairville Petroleum Corp., Westfalls, N.Y.
LOGIT, Software Associates, Westerville, Ohio
Log Analysis, Buckner Project, Houston, Texas
EZ-Log, Geosphere Software, Houston, Texas

Most of these systems were designed for the oil industry. Some have been designed with the mineral industry needs in mind. Several suppliers have also indicated a willingness to make modifications or additions that may be required.

Most of the programs listed are able to perform the types of analyses outlined. From experience, one of these programs, Terralog, can utilize the digital data from almost any tool or source with very little additional effort. Nine track tape is the most flexible medium for data transfer and storage, although floppies

are also used. Experience has shown in other related work that data is needed on a very small increment such as 1 cm. On this basis a drill hole of any substantial depth will generate a very large file.

Geona Enterprises has developed, with the support of the Federal Government, a relatively sophisticated software package for reducing standard geophysical suite data in oil sands to derive a number of geotechnical/hydrogeological parameters including type of pore water, cement volumes, grain size data etc. It would appear that this package could be modified to handle coal and associated overburden logs. Testing of this software is merited.

At a minimum the system chosen for use will require the following abilities:

1) Data entry and Storage capabilities
   - a) multiplex data
   - b) string data
   - c) raw digitized data

2) General Conveniences, such as:
   - a) help commands
   - b) depth setting
   - c) selection of depth frequency
   - d) depth scaling
   - e) metric compatibility
   - f) screen or page annotation
   - g) easy log selection

3) Data Handling
   - a) data base
   - b) files
   - c) functions, such as:
     1) modify one or more logs
     2) compute channel sum
     3) eliminate data outside limits
     4) adjust logs based on compared values
     5) perform selected operations

4) Data Display

a) echo

b) scan

c) status report

d) histogram

e) log plotting

1) define configuration
2) modifications
3) adding and removing curves from display
4) shading
5) reference depth
6) reference lines
7) lithologic column

5) Other

a) crossplots

1) frequency
2) regression
3) zplot
4) three component plots
5) lithodensity plot

b) various output options

6) A sophisticated petrology computation ability

7) The integration of different elements like:

a) those used in classical reservoir analysis,

b) synthetic seismograms,

c) the ability to compute indexes such as rock strength,

d) the ability to merge multiple plots as overlays.

e) sufficient work space to handle at least 50 channels or plots of information

8) The ability to handle and assist in the analysis of dip meter logs

9) General statistical abilities

10) Clear presentation of outputs in a user defined format.

Use one or more of the currently available packages provides a starting point for continuation of this project. It will probably be necessary to write some additional software for specific requirements.

9. SUMMARY AND CONCLUSIONS

9.1 General

The review of the current "state-of-the-art" use of borehole geophysics shows that there are techniques available with the potential to provide some of the geotechnical and hydrogeological parameters desired. Most of these techniques were originally developed for either the petroleum or hard rock applications.

The reliability and effectiveness of these techniques in the shallow, soft rock typical of the western Canadian coal and oil sands mining situations has not been fully evaluated or in some cases even attempted.

Many of the desired parameters can apparently be derived from the geophysical logs currently being obtained by the mining and exploration companies as part of their ongoing programs. These geophysical logs are obtained for identifying lithological and interpreting geological structures. Typical logging suites in the coal and oil sands operations include:

Caliper
Natural Gamma
Gamma-Gamma (Density)
Resistivity (short, long or focussed)

Additional logging has been done including:

Neutron-Neutron
Dipmeter (3 or 4 Point Resistivity)
Sonic

These logs when combined with correlation data from laboratory tests and field tests (uniaxial compressive strength and falling head tests for example) will allow an initial evaluation of many of the techniques without additional field data collection.

9.2 Parameters and Probes

A wide variety of geophysical borehole probes are available, all of which measure a physical characteristic of the material under investigation. This physical characteristic is rarely a direct measurement of the actual parameter of interest but be correlated to the parameter in some manner. For example, a dipmeter does not record the strike and dip of the geologic unit; it measures the resistivity of a small part of the borehole. By combining the three or four resistivities recorded at the same time, a mathematical manipulation can interpret the strike and dip of the various layers in the structure. Many of the geological and hydrogeological parameters will only be derived by combinations of various probes and techniques.

The summary of the literature and current research suggests that the following probes can be used to predict the associated parameters.

The Caliper probe is used mainly to correct the data from other tools for the variations in hole diameter. It can also indicate the structural competence of the various rock types.

The natural Gamma tool provides clay content data which is important in determining lithology, structural features and possibly permeability. Spectral gamma logs provide information on clay minerology.

The Gamma-Gamma (density) tool is the primary tool for determining material density. It can also be useful in interpreting porosity.

Neutron-neutron tools are used extensively in the oil and gas industry for determining porosity and moisture content.

Resistivity logging is currently used for lithological analysis and contact definition but is reported to have potential for determining moisture content and saturation and has been used for water quality.

The dipmeter is a variation on the standard resistivity tool that provides strike and dip measurements of the geologic structure. There may be some possibility of determining joint sets.

Induction logs are most likely to be useful in determining water quality and saturation of surficial materials.

Both the acoustic televiewer and borehole television systems can provide a detailed picture of the borehole wall allowing the geologist to examine bedding, contacts, material types and to make strike and dip measurements.

Radar has the potential, in areas of varying conductance, to map the structures and fractures. Of particular note is its ability to penetrate long distances in suitable materials. Initial indications suggest, however, that the plains overburden materials are poorly suited to this approach.

Radio imaging, both downhole and crosshole, has uses in fracture and fault mapping and lithological determination and correlation.

The various flowmeters can provide information on in-situ water flow, and aquifer idenfitication. Temperature probes and flowmeters provide information on relative yield.

Table 3 provides a quick summary of the various probes and the parameters to which they can contribute information. It is apparent from the literature reviewed that there is no reported technique for determining pore pressure.

9.3 Data Manipulation Software

As most of the techniques are based on the numerical manipulation and combination of the various geophysical logs, a computer software package capable of inputing, sorting and displaying these logs is the only efficient method for fully evaluating these techniques. A key component of a software system for evaluations of this type will be the ability to allow user input of new evaluation approaches or modifications to the currently available models.

TABLE 3
CHART OF APPLICATIONS

Geophysical Tool / Parameter	Caliper	Natural Gamma	Gamma Gamma density	Neutron Neutron	Resist.	3 point Resist. dipmeter	Sonic Tube Wave (VSP)	Gravity	Flow-meter	Temp.	Radar	Holog.	Acousti & Borehol Televi.
Lithology	*	*	*	*	*		*						*
Geological Structure		*			*	*	*				*		*
Density	*		*	*			*	*					
Rock Quality Designation	*			*	*	*	*						
Compressive Strength				*			*						
Shear Strength							*						
Elastic Properties							*						
Stress Distribution												*	
Fractures	*		*			*	*				*		*
Grain Size Dist.		*	*			*							*
Pore Pressure													
Moisture Content			*	*	*					*			
Water Flow									*	*			
Porosity			*	*	*		*						
Permeability		*							*	*			
Water Quality					*								

Note: Any particular parameter may require more than one of the identified tools.

There are several software packages available to handle almost any type of geophysical log. Many of the packages already have manipulations built in to determine some of the desired parameters. These modelling techniques were generally developed for other applications such as oil and gas and may be fully applicable to the coal and oil sands environment with only limited modification.

Selection of specific packages to use for the evaluations will depend on the availability of hardware and suitable logs for the specific evaluations.

10. RECOMMENDATIONS

The following recommendations for further work are made:

1. Select one or two computer software packages and evaluate their ability to reliably produce the desired parameters in the coal and oil sands environments from currently available log and laboratory data. This recommendation is the main component of Phase 2 of the project as originally conceived.

2. Evaluate the cost effectiveness of using these techniques to obtain the hydrogeological and geotechnical parameters.

3. Review and recommend which additional geophysical logging systems have the potential to produce additional parameters in a cost effective manner for which no western Canadian data are available.

4. Continuing contact with other workers in this field should be considered to enable the project to stay current with ongoing developments. Areas of particular interest are pulsed neutron tools, crosshole seismic tomography and acoustic televiewers.

5. Research into geophysical techniques for determining pore pressure should be conducted.

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APPENDIX 1

PROJECT ORGANIZATION AND MANAGEMENT

APPENDIX 1

1. Management Committee

The project is governed by a Management Committee that provides overall direction to the Hydrogeological and Geotechnical Committees conducting the study. This includes responsibility for project content and budget control, as well as responsibility for selection of the final technical and expert committee members.

The following individuals have been appointed to the Management Committee:

D. Nikols, TransAlta Utilities Corporation **(Chairman)**
D. Scott, Civil Engineering Department, University of Alberta
E. Fraser, Suncor Inc.
N. Wade, Monenco Consultants Limited
G. Jenkins, Chairman, Geotechnical Committee, Manalta Coal Limited
A. Hickinbotham, Chairman, Hydrogeological Committee, TransAlta Utilities Corporation
T. Sneddon, Alberta Office of Coal Research & Technology
B. Das, CANMET: Energy, Mines & Resources, Canada

2. Geotechnical Committee

This committee is responsible for the scope of the geotechnical component of the study, technical procedures, and for making recommendations to the Management Committee with regard to selection of competent geophysical and geological professionals to conduct the research.

The following representatives comprise the Geotechnical Committee:

G. Jenkins, Manalta Coal Ltd., **(Chairman)**
B. Das, CANMET: Energy, Mines & Resources, Canada
I. Rozier/P. Stacey, Golder Associates
A. Leach, Klohn Leonoff Ltd.
F. Khan, Terracon Geotechnique Ltd.
N. Wade, Monenco Consultants Limited

3. Hydrogeological Committee

Similarly, the Hydrogeological Committee is responsible for the scope and procedures within the hydrogeological component of the study.

The committee is comprised of the following representatives:

A. Hickinbotham, TransAlta Utilities Corporation, **(Chairman)**
M. Trudell, Alberta Research Council
L. Pitts, Monenco Consultants Limited
N. Worsley, Saskatchewan Power Corporation
T. Dabrowski, Piteau Associates Engineering Ltd.
L. Nichols, Terracon Geotechnique Ltd.
G. Lobb, Syncrude Canada Ltd.

4. Project Manager

The administration of the project and coordination of subcontractors is carried out by the Coal Mining Research Company acting as project manager, under the direction of the Management Committee. Additional responsibilities include technical and financial progress reports to the Management Committee, as well as preparation of project reports.

5. Expert Review Panel

The expert review panel has been selected to review the results of the research conducted during the project and to advise on the content and procedures required in subsequent phases. Panel members include:

S. Keys	United States Geological Survey, Denver, Colorado (Retired)
P. Killeen	Geological Survey of Canada
J. Mwenifumbo	Geological Survey of Canada
C. Brawner	University of British Columbia
N. Morgenstern	University of Alberta
R. Bishop	BPB Instruments, (Canada) Ltd.

APPENDIX 2

KEY WORD LIST

CONCEPT DELINEATION OF KEYWORD LIST FOR
DOWNHOLE GEOPHYSICS RESEARCH PROJECT

(1) GEOPHYSICAL GENERAL

geophysics
borehole geophysics
downhole geophysics
geophysical logs
logs
borehole logs

(2) LOGGING METHODS

well logging (tools)
wireline logging (tools)
nuclear logging
logging tool
seismic
shear wave
borehole televiewer
induction logging
borehole camera

(3) LOG TYPES

sonic log/logging
acoustic log
density log
caliper log
resistivity log
gamma log
electric log
apparent density log
bulk density
gamma-gamma
radioactive log
natural gamma log
fluid log
neutron activation log

(4) GEOPHYSICAL TERMS

dipmeter (diplog)
cycle skipping
crosshole
velocity
wavelet
neutron
geophone
strength index
elastic moduli
dynamic moduli
petro physics
flowmeter
gamma spectrometry
log interpretation
log analysis
synergistic analysis

flowmeter
gamma spectrometry
log interpretation
log analysis
synergistic analysis

(5) HYDROGEOLOGICAL GENERAL

ground water
groundwater
water quality
water chemistry
groundwater chemistry
hydraulic
hydrogeology
hydrogeoligic

(5) HYDROGEOLOGIC PARAMETERS

pore pressure/hydraulic head
hydraulic conductivity
porosity
effective porosity
storativity
specific yield
yield
secondary porosity
permeability
fracture

(7) HYDROGEOLOGICAL TERMS

transmissivitiy
acuifer
equitard
water table
groundwater flow
groundwater conductivity

(8) GEOLOGICAL

geologic
shear plane
glacial throsting
joint orientation
deformation
structure
consolidation
lithology
fracture zones
bedding
subsurface
core
faults
folds
texture
cementation
hardness
permeability
stratigraphy
cementation

hardness
permeability
stratigraphy
cementation

(9) SOIL MECHANICS

geotechnical
soil strength
in situ
preconsolidation
compaction
effective stress
liquid limit
Atterberg limits
failure criteria
Mohr's circle
shear strength
compressive strength
cohesion

(10) ROCK MECHANICS

geomechanical
rock strength
rock mechanics
rock fabric
competency
strength properties
stress
durability
elasticity
dynamic properties

(11) MINING TERMS

mine engineering
slope stability
blasting
diggability
trafficability
slope failure
highwall failure
landslide
footwall
seatearth
strip mining
open cast
mine planning
coal mining

(12) OILSANDS TERMS

tar sands
oil sands

APPENDIX 3

BOREHOLE GEOPHYSICAL EQUIPMENT

DOWNHOLE GEOPHYSICAL LOGS(GENERIC):

Electrical Methods:
Single point resistance
Resistivity (40,80 & 160 cm separations)
Spontaneous potential
Fluid resistivity
Focused beam resistivity
VLF-EM (very low frequency electromagnetic)
Radar; single hole and crosshole
Electromagnetic; single hole or crosshole
Electromagnetic; surface to downhole
Dipmeter
Induced Polarization

Radiometric Methods:
Natural gamma; broadband or spectrometry
Density (gamma-gamma)
Porosity (neutron-neutron)

Seismic Methods:
Sonic; velocity, amplitude and full waveform
Tube waves; surface to downhole
Crosshole seismic (can include tomography)

Thermal Methods:
Temperature Measurements
Heat-pulse flowmeter

Others:
Aquifer Tide

Impulse Flowmeter

Television:

Acoustic Televiewer:

Magnetic Susceptibility

Caliper

GEOPHYSICAL LOGGING EQUIPMENT (BY MANUFACTURER):

APPLIED ELECTRONICS LTD.,
299 Evans Ave., Toronto.M8Z 1K2.
Tel: 416 252-3761.

Agent for Rees television system of UK.

BISON INSTRUMENTS INC.,
5708 West 36th Street,
Minneapolis. Minn. 55416 USA
Tel: 612 926-1846.

Crosshole Shear Wave System:
The system consists of shear wave hammer, geophones and engineering seismograph. Dynamic moduli of the rock volume can be computed. 60 m operable length; up to 30 m hole seperation.
Also Magnetic susceptibility equipment.

COMPROBE, INC.,
9632 Crowley Rd. Crowley,Tx, 76036.USA.
Tel 817 293-7333.

Natural gamma, neutron, temperature, differential temperature, fluid resistivity, caliper, density; up to 4500 m cable length; 1, 4 or 7 conductor; digital capabilities on 9-track tape, an LSI-11 based system; variable tool diameter, but most less than 75 mm.

EASTMAN
P.O. Box 1160,
Carl-Zeiss-Strasse 16,
3005 Hannover - Westerseld,
West Germany.

Borehole television system

Geologger-3000:
Resistivity, microresistivity, spontaneous potential, temperature, caliper, density, natural gamma, magnetic susceptibility; 4 conductors; 310 m length; not known whether digital recording is possible; all tools of diameter less than 50 mm.

Geologger-3400:
Natural gamma, single-point resistance, spontaneous potential, density, resistivity, temperature and differential temperature, caliper, fluid resistivity and sonic velocity; limited digital storage capability, details unknown; all tools except sonic of 32 mm diameter, sonic of 46 mm diameter.

EG&G GEOMETRICS MOUNT SOPRIS DIV.
P.O. Box 449, Delta.Colo. 81416.
Tel: (303) 874-5711.

Model 1000-C:
Backpack portable; single-point resistance, spontaneous potential and natural gamma are the basic logs available on this system. Some other probes e.g, density, porosity and spectral gamma can also be attached after modifications. No digital capabilities. 300 m cable; single conductor. Probe diameter 50 mm or less

Model II:
Lightweight system of weight about 100 kg. Sonic, flowmeter, fluid resistivity, gamma, density, porosity, resistance, resistivity,focussed-beam resistivity, temperature and caliper are available. Cable up to 760 m. Digital recording on cassette and possibly floppies. Most tools of diameter 60 mm or less.

Model III:
Sonic amplitude, transit time and full waveform; borehole deviation (magnetic), caliper, dipmeter, fluid resistivity, induced polarization (time domain), induction, natural gamma, resistance, 40-and 80-cm resistivity, single and dual spaced gamma-gamma, spontaneous potential, spectral gamma, temperature, thermal neutron and other specialized tools. Fully digital, on cassettes, floppies or nine track; can be mated to a micro or a mini. Most tools of diameter less than 50 mm; some up to 60 mm. 4-conductor cable up to 3 000 m. Has to be truck mounted.

IBAK
Wehdenweg 122; Postsach 6260,
D-2300 Kiel 14. West Germany.

Downhole television system; colour capability.

MCPHAR RADIOMETRICS,
Tel: 416 477-5766.

Multilog-3:
Natural gamma, single-point resistance, self-potential.; single conductor; 350 m length; no digital capabilities; 32 mm tool diameter; backpack portable. (Currently not in production).

RD-600:
Spectral gamma, self potential, single-point resistance and resistivity. Digital recording, mated to LSI 11 computer.
It has been reported that McPhar is also developing a temperature logger.

MINERAL LOGGING SYSTEMS, INC.
8821C Forum Way, P.O. Box 40498,
Fort Worth, TX 76140, USA.
Tel: 817 293-1777.

Natural gamma, neutron, density, temperature, flowmeter, sonic, caliper, fluid resistivity, focussed beam, resistance; digital recording, on cassette mated to a Hewlett Packard 85 computer; length up to 4 000 m; most tools less than 50 mm diameter. Various " series" are possible by combination and permutation of components.

OYO CORPORATION, INSTRUMENTS DIV.,
2-19 Daitakubo 2-Chome, Urawa,
Saitama 336 Japan. Tel 0488-82-5371
In Canada:
Romor Equipment Ltd., 1083 Britannia Road E.
Mississauga.Ont.L4W 3X1. Tel 416-671-3209

Geologger-300:
Very light (6 kg) backpack portable; resistivity, spontaneous potential. Temperature and caliper also possible. Single conductor. No digital capability. 310 m cable length. Tools of less than 50 mm diameter.

ROBERTSON RESEARCH ENGINEERING SERVICES LTD; GEOLOGGING DIV.,
TY'N-Y-COED, LLANRHOS,
LLANDUDNO; GWYNEDD LL301SA,UK.
Tel: (0492) 81811.

Geolog 1000:
Natural gamma, dual density, fluid resistivity, temperature, density, 40-, 80- and 160-cm resistivity, focussed-beam resistivity, flowmeter (impeller and heat-pulse), caliper, and other specialized tools. Most tools less than 50 mm diameter. Length 1000 m. Four conductor cable. Fully digital. Recording on cassettes and possibly other media.

SCINTREX LTD.,
222 Snidercroft Road, Concord.Ont.L4K 1B5.
Tel: 416 669-2280

Borehole logging systems are not the principal products of Scintrex. However, a perusal of their catalogue shows that they offer the following products: spectral gamma; electromagnetic borehole logging; induced polarization/resistivity and a specialized tool the "metalog", which could be modified to yield ash content in coal.

SHIMUZU CONSTRUCTION CO.
Tokyo, Japan.
Borehole television system; colour capabilities.

SIMPLEC MANUFACTURING CO INC.,
4230 Shilling Way,
Dallas. Texas. 75237. USA.
Tel 214 330-0406.

Acoustic televiewer system. Cable length up to 2 000 m.

SOLINST CANADA LTD.,
5 - 2440 Industrial Street,
Burlington. Ont. L7P 1A5.
Tel: 416 335-5611

Downhole television system.
Il tools of diameter less than 50 mm.

Geologger-3400:
Natural gamma, single-point resistance, spontaneous potential, density, resistivity, temperature and

GEOPH.LOGGING RESEARCHERS (BY INSTITUTION):

ATOMIC ENERGY OF CANADA LIMITED.,
Applied Geoscience Branch, Whiteshell Nuclear Research Establishment, Pinawa. Man. R0E 1L0.
Principal Contact: Dr. Nash Soonawala.
Tel 204 753-2311.

Dzintars K. Tomsons, N. Soonawala, general logging; Mt.Sopris Model I and Model III.

Peter Hurley; crosshole seismics, tomography; fully operational equipment developed by AECL/U of Toronto.

Cheng F. Huang; tube waves; fully operational equipment developed by AECL/GSC.

John G. Hayles; VLF-EM.

Joe Lau; borehole television and acoustic televiewer. Sperry and Simplec equipment.

Cliff C. Davison; hydrogeological applications.

GEOLOGICAL SURVEY OF CANADA

Dr. Patrick G. Killeen, Exploration Geophysics Subdivision, Mineral Resources Div., Geological Survey of Canada, 601 Booth Street, Ottawa. Ont. K1A 0E8. Tel:613 996-2312.
Expert in general logging; primary interest, nuclear logging; mostly nuclear equipment of own design or heavily modified.

Dr. Jonathan Mwenifumbo, same address as above.
Electrical methods; experimental equipment, mostly mise a la masse.

Dr. Malcolm Drury, Geothermics, Geophysics Div., Geological Survey of Canada, 1 Observatory Cresc. Ottawa. K1A 0Y3.
Tel 613 995-5478.
Thermal logging; portable thermal logger.

Leonard S. Collett, 601 Booth Street, Ottawa K1A 0E8
Tel: 613 993-5964
General logging, radar.

Don Bower, Geophysics Div.,
Geological Survey of Canada,
1 Observatory Cresc. Ottawa. K1A 0Y3

GEOSEISMO OY
Valimotie 23C, SF-00380 Helsinki,Finland
Calim G. Cosma, crosshole seismics.

INSTITUTE OF GEOLOGICAL SCIENCES,
Building 151,
Harwell Laboratory, Oxon. OX11 ORA. UK
Dr. David M. McCann; crosshole seismics.

ISMES,
Via T. Taramelli 14,
I-00197 Rome, Italy
Dr. F. Gera; crosshole seismics.

JODEX APPLIED GEOSCIENCE,
40 McGillvray Av.
Toronto. M5M 2Y1. Tel: 416 483-7724.
Dr.Joe Wong, full waveform sonic, crosshole seismic, tomography. Will provide logging services, and might manufacture and sell downhole equipment.

LAWRENCE LIVERMORE NATIONAL LABORATORY
P.O. Box 808,
Livermore. Calif. 94550. USA.
Dr. Abe Ramirez; Tel 415 422-6909; electromagnetic tomography.

MCGILL UNIVERSITY
Dept. of Geological Sciences,
Montreal. H3C 3G1.
Tel: 514 392-5950
Contact: Dr. W.Murray Telford;
Dr. Jean Roy, presently overseas, general logging; VLF-EM.

QUEEN'S UNIVERSITY,
Dept. of Geological Sciences,
Kingston. Ont. K7L 3N6.

Dr. Paul Young; crosshole seismics tomography. Tel:613 547-2798.

Dr. Alfred V. Dyck, electrical methods.

SOUTHWEST RESEARCH INSTITUTE,
6220 Culebra Road,
San Antonio. Texas. 78023.
Contact: Tom Owen (512)684-5111
Radar, and numerous other geotechnical methods.

SWEDISH GEOLGICAL CO.
Box 1424, 75144 Uppsala, Sweden.
Dr. Olle Olsson; radar logging, also possible contact for crosshole seismic. Tel:018-156420

UNITED STATES GEOLOGICAL SURVEY.
Dr. Frederick L. Paillet, Borehole Geophysics Research Project, USGS, MS 403, Denver Federal Center, Denver. Colo. 802205.
Tel: 303 236-5913.
General logging, full waveform sonic, heat-pulse flowmeter; very sophisticated equipment.

Dr. David Wright, USGS, MS964,
Denver Federal Center, Denver. Colo. 80225.
Tel: 303 234-5462.
Radar logging; self-designed and developed equipment.

UNIVERSITY OF TORONTO
Dept. of Physics,
Toronto. M57 1A7

Dr. Gordon F. West, crosshole seismics, electromagnetic induction methods; Tel 416 978-3155.
Ken Howard, general logging.

UNIVERSITY OF WATERLOO
Dr.John Greenhouse, logging in overburden.

APPENDIX 4

EQUIPMENT SUPPLIERS, CONTRACTORS AND RESEARCHERS

A: Equipment Supplier & Contractors

B: Researchers

A: EQUIPMENT SUPPLIERS AND CONTRACTORS

COMPANY	CONTACT & TELEPHONE
A-Cubed 5566 Tomkem Road Mississauga, Ontario L4W 1P1	Dr. A.P. Annan (416)624-8878
Alpha Nuclear 6380B Viscount Road Mississauga, Ontario L4V 1H3	Jeff Denham (416)676-1364
Atomic Energy Canada Ltd. Pinawa, Manitoba	Dr. N. Soonawala (204)753-2311
BPB Instruments Ltd. 5915C - 36th Street S.E. Calgary, Alberta	Richard Bishop (403)234-9144
Century Geophysical Corporation of Canada 5911 - 5th Street S.E. Calgary, Alberta	Andrew Cicoria (403)255-1110
CGG Suite 300, 2500 Wilcrest Houston, Texas 77042	(713)784-0740
Comprobe Instruments 6932 Crowley Road Crowley, Texas 76036	Glen Breaux (817)293-7333
Computalog Gearhart Ltd. 1917 - 84 Avenue Edmonton, Alberta	Philip Hnatiuk (403)464-6107
Crone Geophysics Ltd. 3607 Wolfedale Road Mississauga, Ontario L5C 1V8	Duncan Crone (416)270-0096
Delft Soil Mechanics Laboratory Stieltjesweg 2 P.O. Box 69 2500 AB Delft The Netherlands	M. Kroezen 015-569223 Telex: 38234 Solabnl

A: EQUIPMENT SUPPLIERS AND CONTRACTORS (cont'd)

COMPANY	CONTACT & TELEPHONE
Dresser-Atlas 1200, 505 - 3rd Street Calgary, Alberta	Jerry Manly (403)290-5100
EG & G Geometric Mt. Sopris Instruments Division P.O. Box 449 Delta, Colorado 81416	John Stowell (303)874-5711
Exploranium 55 Healey Road, Unit 5 Bolton, Ontario L7E 5A2	John Cox (416)857-3670
Gearhart Industries P.O. Box 1936 Fort Worth, Texas 76101	
Geonic Limited 1745 Meyerside Road Unit #8 Mississauga, Ontario	J.D. McNeill (416)676-9580
Geotech 20-101 Amber Street Markham, Ontario L3R 3B2	Scott Holladay (416)473-6999
Huntec (70) Limited #303, 3130 Lawrence Aven. East Scarborough, Ontario M1R 5C7	Jack Dodds
I.F.G. 18 Bram Court Unit 5 Brampton, Ontario L6W 3R6	Detlef Blohm (416)451-5228
Keck 1099 West Grand River Willianston, Michigan 48895	Dan Tuttle (517)655-4391
Lamontagne Geophysics Ltd 49 Spadina Ave. Toronto, Ontario M5V 2J1	Y. Lamontagne (817)293-7333

A: EQUIPMENT SUPPLIERS AND CONTRACTORS (cont'd)

COMPANY	CONTACT & TELEPHONE
McPhar Geophysics 3400 - Fourteenth Street Markham, Ontario	Bradley Stevens (416)477-5766
Mineral Logging Systems Subsidiary of Gearhart Industires 8821C Forum Way P.O. Box 40498 Fort Worth, Texas 76140	Charles Dickson (817)293-1300
Neltronic Instrument Corp. 4319 Stanford Houston, Texas 77006	Frank Geraghty (713)523-2546
OYO Corporation Instruments Division 2-19 Daitakubo 2 - Chome, Urawa Saitama 336 Japan	0488-83-5371
OYO Corporation (Canadian Representative) Romor Equipment Ltd. 1083 Britannia Road E. Mississauga, Ontario L4W 3X1	Robert Morgan (416)671-3209
Phoenix Geophysics Ltd. 200 Yorkdale Blvd. Willowdale, Ontario M2J 1R5	P.G. Hallof (416)477-8588
Robertson Research Eng. Services Llandudno Gwynedd LL301SA, U.K.	R.G. Williams (0492)81811
Roke Oil Enterprises Ltd. 516 Moraine Road N.E. Calgary, Alberta	Keith Banks (403)273-5553
Schlumberger 801 - 6th Ave. Calgary, Alberta	Mike Standford
Scintrex 222 Snidercroft Road Concord, Ontario	Dr. S. Nargolwolla (416)669-2280

A: EQUIPMENT SUPPLIERS AND CONTRACTORS (cont'd)

COMPANY	CONTACT & TELEPHONE
S.G.A.B. Swedish Geological Box 1424, S-751 44 Uppsala, Sweden	Mr. O. Olsson
SIE Division of Geosource Inc. 105 - 61671 Ave. S.E. Calgary, Alberta	Don Farney (Calgary) (403)253-2135
Simplec Manufacturing Co., Inc. 4230 Schilling Way Dallas Texas 75237	George Cimpoz (214)330-0406
Stolar 2715 - J Broadbend Parkway Albuquerque, New Mexic 87107	Bill Mondt (505)345-7871
Urtec Instrument Sales Ltd. 131 Telson Road, Unit 6 Markham, Ontario M4T 1N6	Frank Bottos (416)475-1133

B: RESEARCHERS

CONTACT	COMPANY
Mr. James N. Albright Deputy Group Leader, ESS-4 P.O. Box 1663, Mail Stop J979 Los Alamos, New Mexico 87545	Los Alamos National Laboratory
Mr. Neil J.B. Andersen Project Head Geophysics P. Bag X256 Pretoria, South Africa	Nuclear Development CO. Pty. Ltd. (Nucor)
Mr. Andrew Black Geophysicist 605 Parfet Street Denver, Colorado	EDCON
Dr. Mihai Borsaru Senior Research Scientist 339 Wiliamstow Road P.O. Box 124 Port Melburne, Vic. 3207 Australia	CSIRO, Div. of Mineral Physics
Don Bower Geophysics Div. 1 Observatory Crescent Ottawa, Ontario K1A 9Y3	Geological Survey of Canada
Mr. Quentin Bristow, Head Instrumentation R & D Section Resource Geophysics and Geochemeistry Division 601 Booth Street, Room 579 Ottawa, Ontario K1A 0E8	Geological Survey of Canada
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